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ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΑΛΕΞΑΝΔΡΟΥ Φ. ΤΟΥΛΟΥΖΑ

Επιβλέπων: Ιωάννης Αβαριτσιώτης
Καθηγητής Ε.Μ.Π.

Αθήνα, Σεπτέμβριος 2003

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Εγκρίθηκε από την τριμελή εξεταστική επιτροπή την 19η Σεπτεμβρίου 2003.

………………………	………………………	……………………………
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Αθήνα, Σεπτέμβριος 2003

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ΑΛΕΞΑΝΔΡΟΣ Φ. ΤΟΥΛΟΥΖΑΣ

Διπλωματούχος Ηλεκτρολόγος Μηχανικός και Μηχανικός Υπολογιστών Ε.Μ.Π.

I would like to take this opportunity to thank my thesis advisor, Mr. John Avaritsiotis, for all the valuable help he provided during the implementation of this final year thesis project, the patience he exhibited, and the indispensable advice given in order to overcome the various difficulties that were encountered. The measurements for this thesis project were taken in the Microelectronics Laboratory of the Electrical and Computer Engineering Department of the National Technological University of Athens, Greece. I would also like to thank everyone from the Microelectronics Laboratory that assisted me during the course of this thesis project.

ABSTRACT

The goal of this final year thesis project is to investigate the use of a custom made cylindrical capacitor as a sensor, which is constructed from two concentric copper pipes. The varying dielectric constant of the liquid placed between the two pipes of the capacitor and the resulting change in the capacitance will be the basis of the measurements taken.

The various circuits that are necessary for the sensor's operation and which will inter work with it will also be studied and analyzed. This analysis will determine which circuits are most suited to the required specifications and it will also determine which ones yield optimum results. A microcontroller will be used to control these circuits, and to collect the output from the sensor that will be displayed accordingly.

Finally, the actual characteristics of the capacitor will be analyzed to determine how the measurements taken compare to the theoretical values calculated. Any discrepancies found will be explained and possible improvements, if any are required, will be suggested. In conclusion, several sample applications of such a type of sensor coupled with a microcontroller will be discussed.

KEY WORDS

Capacitor, Dielectric Constant, Microcontroller, 555-Timer, Transistor Switching Circuits, Sensor.

Περίληψη

Ο σκοπός αυτής της διπλωματικής εργασίας είναι η διερεύνηση ενός πυκνωτή σε σχήμα κυλίνδρου κατασκευασμένος από δυο ομόκεντρους χάλκινους σωλήνες που θα χρησιμοποιηθεί ως αισθητήρας. Η μεταβαλλόμενη διηλεκτρική σταθερά του υγρού το οποίο θα τοποθετηθεί μεταξύ τους δυο ομόκεντρους σωλήνες, και η διαφορά στην χωρητικότητα που προκύπτει θα είναι η βάση των μετρήσεων που θα συλλεχθούνε.

Τα διάφορα βοηθητικά κυκλώματα τα οποία είναι απαραίτητα για την λειτουργία του αισθητήρα θα ερευνηθούνε και θα εξεταστούνε. Η ανάλυση αύτη θα προσδιορίσει πια κυκλώματα είναι τα πλέον κατάλληλα για της απαιτούμενες προδιαγραφές, όπως επίσης και πια κυκλώματα αποφέρουν τα καλύτερα δυνατά αποτελέσματα. Ένας μικροελεγκτής θα χρησιμοποιηθεί για των έλεγχο των κυκλωμάτων αυτών όπως και για της μετρήσεις από την έξοδο του αισθητήρα η οποία θα επιδεικνύεται ανάλογα.

Επίσης, τα ακριβή χαρακτηριστικά του πυκνωτή θα αναλυθούνε για να αξιολογηθούνε οι μετρήσεις που καταγράφθηκαν σε σύγκριση με της θεωρητικές τιμές που υπολογίσθηκαν. Θα γίνει επεξήγηση για όποιες ασυμφωνίες προκύψουνε μεταξύ της μετρήσεις και της θεωρητικές τιμές, και θα υποδειχθούνε πιθανές βελτιώσεις, αν χρειάζονται. Ολοκληρώνοντας, μερικά παραδείγματα θα προταθούνε για καθημερινές εφαρμογές ενός τέτοιου τύπου αισθητήρα σε συνεργασία με έναν μικροελεγκτή.

Λέξεις Κλειδιά

Πυκνωτής, Διηλεκτρική Σταθερά, Μικροελεγκτής, 555-Timer, Μεταγωγικά Κυκλώματα τρανζίστορ, Αισθητήρας

TABLE OF CONTENTS

1. INTRODUCTION

Various types of sensors can be found all around us in almost every electronic device that we use. These sensors can be as simple as a thermostat in a refrigerator and a water heater or as complex as the speed measurement sensors in a particle accelerator. Sensors are commonly used as an input to control a type of device, and the sensitivity of a sensor determines its overall precision and usually its cost as well.

Microcontrollers are increasingly being used for a wide variety of tasks, as an abundant variety of compact and economical models is available on the market. This allows a designer to use a sensor and a microcontroller to control almost anything he can think of. As most microcontrollers cannot handle large currents, a relay can be added to solve this problem, thus allowing for an unlimited amount of ideas that can be developed.

The scope of this final year thesis project is to develop a sensor whose output will be connected to a microcontroller that will display the readings taken. The sensor will operate as a capacitor and the capacitive fluctuations generated by the variable height of the dielectric will be measured. Three qualities of a typical sensor, linearity, sensitivity, and discreteness will be analyzed so that the overall performance of the sensor can be determined.

2. THEORY OF SENSOR OPERATION

The capacitance of a capacitor is determined by two factors: The geometry of the conductors that it is constructed of and the permittivity of the medium between these conductors. When a DC voltage is applied across the conductors of a capacitor, a transfer of charge occurs with +Q on one conductor and –Q on the other[1].

For this project, a cylindrical capacitor will be used as a sensor. This capacitor will consist of two conductors, one with an inner conductor of radius ***a*** and an outer conductor of radius ***b***. The length of the capacitor will be ***L***, and the area between the two conductors will either consist of free space or it will be filled with a dielectric medium whose permittivity is ***ε***. Figure 1 below depicts the cylindrical capacitor geometry[1].

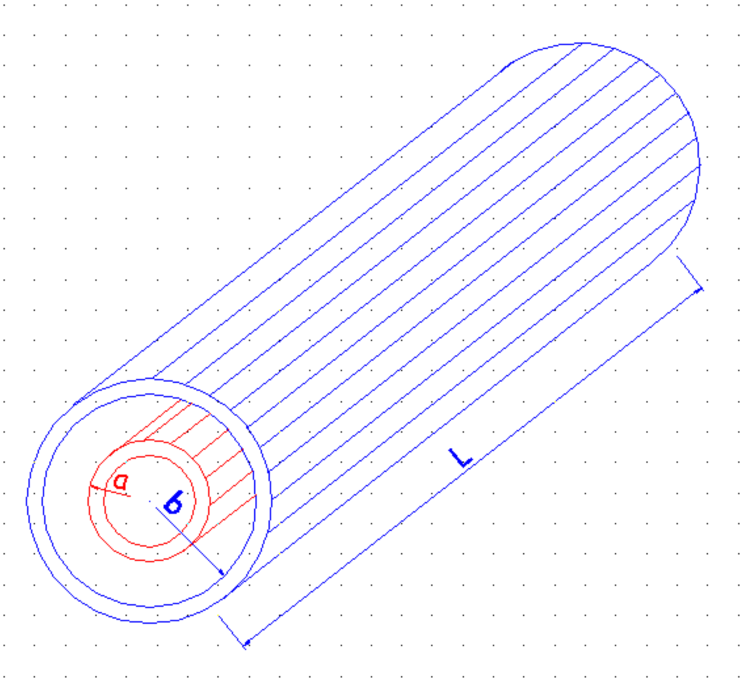

Figure 1

By applying Gauss's Law to the cylindrical Gaussian surface within the dielectric, the ***E*** field can be obtained[1]. This results in:

$$E = a_r E_r = a_r \frac{Q}{2\pi \varepsilon L r}$$

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[1] Field and Wave Electromagnetics

The potential difference between the inner and outer conductors is[2]:

$$V_{ab} = -\int_{r=b}^{r=a} E \bullet dl = -\int_{b}^{a} \left(a_r \frac{Q}{2\pi\varepsilon Lr} \right) \bullet \left(a_r dr \right) = \frac{Q}{2\pi\varepsilon L} \ln\left(\frac{b}{a} \right)$$

And the resulting capacitance for the cylindrical capacitor is[2]:

$$C = \frac{Q}{V_{ab}} = \frac{2\pi\varepsilon L}{\ln\left(b/a \right)}$$

The capacitor's discharging time will be the characteristic used and the basis of the sensor's operation for this project. After the capacitor is initially charged to a certain potential, it may be allowed to discharge by placing a resistor in parallel with it. The product of ***R*** and ***C*** yields the time constant of the circuit and it is this time constant that determines the amount of change in the potential over a specific period of time. The formula below represents the voltage of the capacitor discharging through a resistor in relation to time ***t***. [3]

$$v(t) = V_o e^{-t/RC} \qquad t \geq 0$$

Similarly, the equation for the charging of a capacitor from an initial potential of 0V is the following.[4]

$$v(t) = V_{VoltageSource}(1 - e^{-t/RC})$$

---

[2] Field and Wave Electromagnetics

[3] Electrical Engineering: Concepts and Applications

[4] Experiment 4 "RC Circuits"

By increasing or decreasing the total capacitance, the time required to discharge the capacitor varies. Similarly, if **t=0** is the time at which the discharging begins, at a constant interval **$t=t_1$** the voltage **$v(t_1)$** will vary accordingly as well. This can be seen in the graph below where time versus voltage is plotted for 2 different RC values. **V_o** is set to 50V and the time from **$0<t<45$** represents the charging of a capacitor, **$45<t<55$** represents the stable state of a fully charged capacitor and **$55<t<120$** represents the discharging of a capacitor. At **t=70**, **v(70)** will be approximately 5V for one RC constant and approximately 15V for another RC constant.

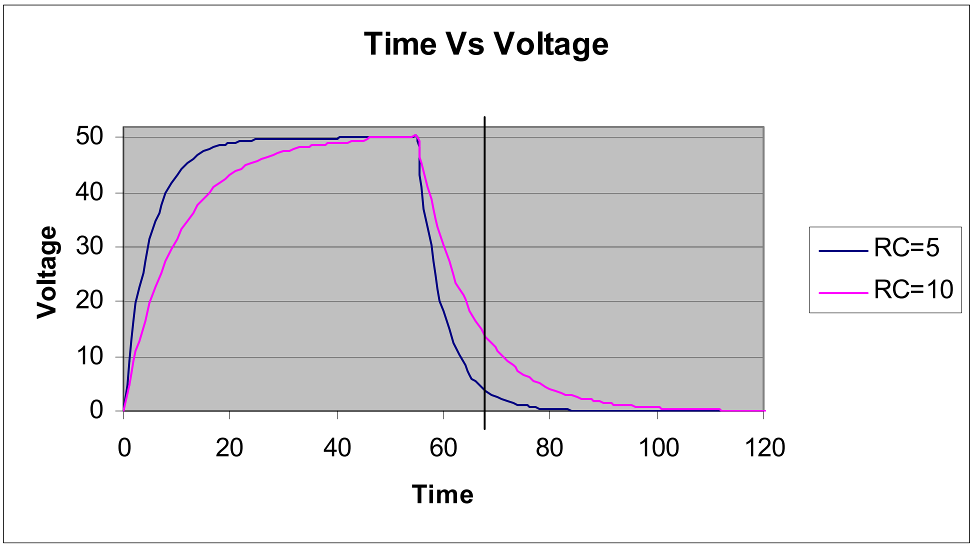

Figure 2

The simple circuit shown below can be used to charge and discharge a capacitor:

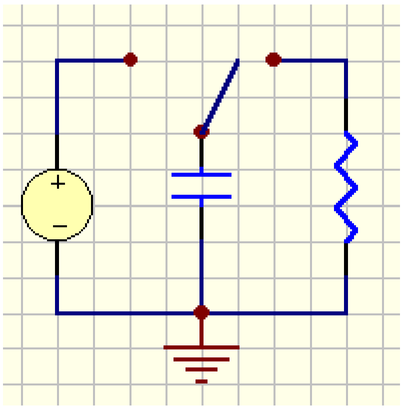

Figure 3

3. CAPACITOR GEOMETRY CALCULATIONS

The capacitor geometry that was used in this project is based on materials that were available in the local market. A cylindrical configuration was selected, as a capacitor can be constructed from two copper pipes, one of a small diameter inserted and centered into a larger diameter copper pipe. Plain copper pipes (1mm thickness) commonly installed in household plumbing installations were used. The following table lists the diameters that were available in the local market.

Ø12mm
Ø15mm
Ø18mm
Ø22mm
Ø28mm
Ø35mm
Ø42mm
Ø54mm

Table 1

As one can see, a great number of combinations were possible and each was examined so as to determine if it could be used. Two restrictions were set in order to simplify the task of determining the final capacitor geometry. The first restriction was that the total capacitance should be approximately 10nF. The reasoning behind this was to have a resulting RC constant that was measurable. The second restriction was that the total length of the capacitor should not be longer than 100cm. This restriction was placed so as to have a length that was easy to work with while still being able to divide the total length in as many 5cm sections as possible, thus yielding many measuring points.

Using the following formula for the cylindrical capacitor, as discussed in the previous section, yielded the following:

$$C = \frac{2\pi \varepsilon L}{\ln\left(b/a\right)}$$

where the permittivity ε was the product of the permittivity of free space, ε_o, and the relative permittivity of the dielectric used, ε_r:[5]

$$\varepsilon = \varepsilon_o \varepsilon_r = \frac{1}{36\pi} \times 10^{-9}\, F/m \times \varepsilon_r = 8.85\, pF/m \times \varepsilon_r$$

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[5] Field and Wave Electromagnetics

By choosing a different dielectric, it was possible to determine the characteristics of the capacitor. For the specific cylindrical capacitor geometry, the dielectric had to be in a liquid form, as the two concentric copper pipes were fixed together with insulating rubber washers in order to ensure a uniform dielectric thickness and to prevent short circuits. A dielectric such as oil would require thorough cleaning after each use in order to ensure accurate measurements. Considering the construction of the cylindrical capacitor, this would have been a very difficult task, thus oil was not used. Other dielectrics like alcohol or diesel fuel presented fire safety hazards and for this reason they were not considered. By default, one of the dielectrics was air. Distilled water and seawater were the other two candidate dielectrics as they were easy to find and work with. Even though oil was not used, the calculations will be presented for comparison purposes only. The relative permittivity constants of the dielectrics are the following[6]:

$$\begin{aligned}
&\varepsilon_r(air) = 1.00 \\
&\varepsilon_r(oil) = 2.30 \\
&\varepsilon_r(distilled\_water) = 80.0 \\
&\varepsilon_r(seawater) = 72.0
\end{aligned}$$

thus resulting in the following permittivities:

$$\begin{aligned}
&\varepsilon_{air} = 8.85\, pF/m \\
&\varepsilon_{oil} = 20.4 pF/m \\
&\varepsilon_{distilled\_water} = 708\, pF/m \\
&\varepsilon_{seawater} = 638\, pF/m
\end{aligned}$$

In order to calculate the capacitance using all of the possible copper pipe combinations, **L** was set to ***L***=100cm and ***ε*** was set equal to the respective permittivity constant. The radius of the inner copper pipe was ***a*** and the outer dimension of the copper pipe was used. The radius of the outer copper pipe was ***b*** and the inner dimension was used. As the copper pipes had a thickness of 1mm, the inner dimensions of **b** were 2mm less than the diameters listed in table 1.

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[6] Field and Wave Electromagnetics

The resulting capacitances can be found in table 2 listed below. The values for oil as a dielectric are listed for comparison purposes only. This dielectric was not used for reasons described earlier.

Inner Pipe		**Outer Pipe**			**Capacitance (nF)**			
Ø(a) (mm)	r(a) (mm)	Ø(b) (mm)	r(b) (mm)	**b/a**	Air	Oil	Sea Water	Water
12	6.0	13	6.5	**1.083**	0.695	1.598	50.019	55.577
12	6.0	16	8.0	**1.333**	0.193	0.445	13.917	15.463
12	6.0	20	10.0	**1.667**	0.109	0.250	7.838	8.708
12	6.0	26	13.0	**2.167**	0.072	0.165	5.178	5.753
12	6.0	33	16.5	**2.750**	0.055	0.126	3.958	4.397
12	6.0	40	20.0	**3.333**	0.046	0.106	3.325	3.695
12	6.0	52	26.0	**4.333**	0.038	0.087	2.730	3.034
15	7.5	16	8.0	**1.067**	0.862	1.982	62.035	68.928
15	7.5	20	10.0	**1.333**	0.193	0.445	13.917	15.463
15	7.5	26	13.0	**1.733**	0.101	0.233	7.279	8.087
15	7.5	33	16.5	**2.200**	0.071	0.162	5.078	5.642
15	7.5	40	20.0	**2.667**	0.057	0.130	4.082	4.535
15	7.5	52	26.0	**3.467**	0.045	0.103	3.220	3.578
18	9.0	20	10.0	**1.111**	0.528	1.214	37.999	42.222
18	9.0	26	13.0	**1.444**	0.151	0.348	10.888	12.097
18	9.0	33	16.5	**1.833**	0.092	0.211	6.605	7.339
18	9.0	40	20.0	**2.222**	0.070	0.160	5.014	5.571
18	9.0	52	26.0	**2.889**	0.052	0.121	3.774	4.193
22	11.0	26	13.0	**1.182**	0.333	0.766	23.966	26.629
22	11.0	33	16.5	**1.500**	0.137	0.315	9.874	10.971
22	11.0	40	20.0	**1.818**	0.093	0.214	6.697	7.441
22	11.0	52	26.0	**2.364**	0.065	0.149	4.654	5.171
28	14.0	33	16.5	**1.179**	0.338	0.778	24.367	27.075
28	14.0	40	20.0	**1.429**	0.156	0.359	11.225	12.472
28	14.0	52	26.0	**1.857**	0.090	0.207	6.468	7.186
35	17.5	40	20.0	**1.143**	0.416	0.958	29.983	33.314
35	17.5	52	26.0	**1.486**	0.140	0.323	10.113	11.237
42	21.0	52	26.0	**1.238**	0.260	0.599	18.746	20.829

Table 2

The graphs depicted by figures 4 and 5 show the relationship between the capacitance versus the ratio of b/a. Figure 4 shows the capacitances for a cylindrical capacitor filled with distilled water and seawater respectively while figure 5 shows the capacitance for a cylindrical capacitor filled with air and oil respectively.

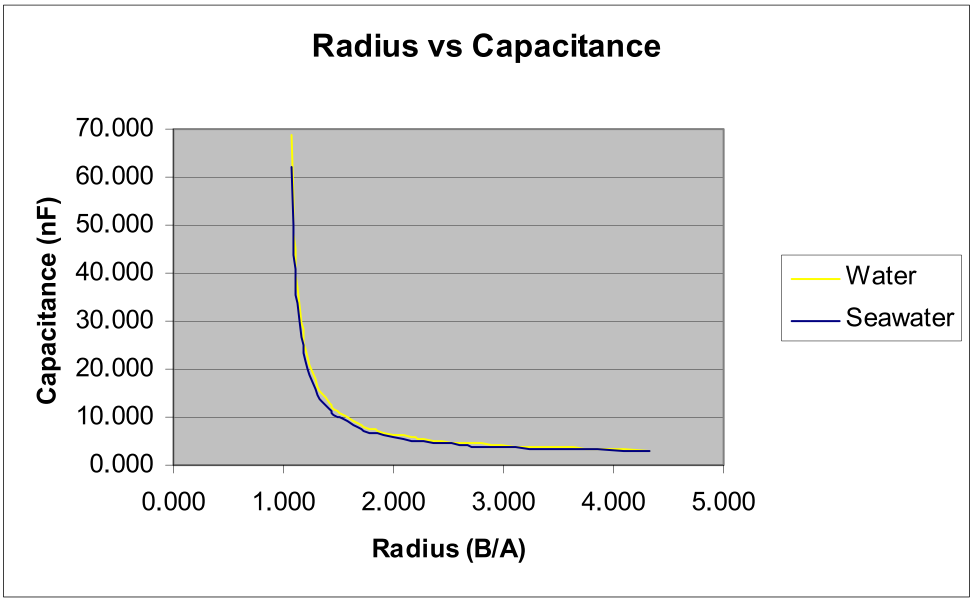

Figure 4

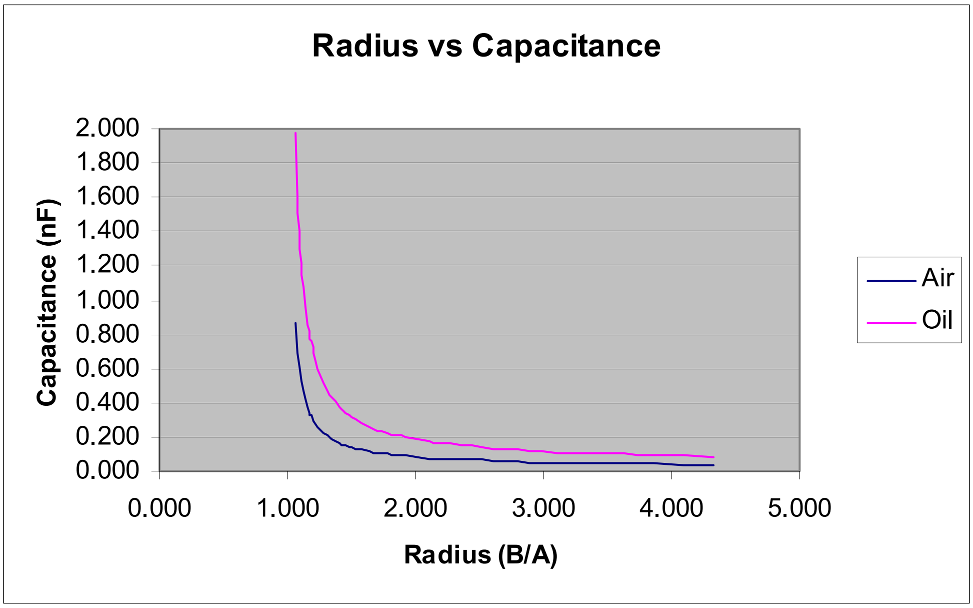

Figure 5

The first conclusion that can be made is that a cylinder filled with air or oil cannot meet the conditions set previously (C=10nF, L=100cm) as the resulting capacitance is between 0.05nF to 0.90nF and 0.10nF to 2.00nF respectively. In order to construct a cylindrical capacitor filled with air that had a capacitance of approximately 10nF, the resulting length would have to be anywhere between 33 to 152 meters, depending on the ratio of b/a that was used. Constructing such a capacitor would not be feasible as it would be very hard to work with an apparatus of such length. Also, there are inherent difficulties in constructing such a capacitor as the longest copper pipe available on the market is 3 meters in length, thus these sections would have to be soldered together to produce the desired length. The soldered connections would alter the geometry, as the diameter would be different at the joints. These diameter variations would also alter the capacitance as the ratio of ***b*** to ***a*** would not be uniform. An argument would be to use the copper pipes that are available on the market in a rolled up coil whose total length exceeds the 3 meters that the straight copper pipes are available in. Using these copper pipes would require straightening them manually, a task that cannot guarantee a perfectly straight copper pipe. The resulting irregularities would produce segments of the capacitor with difference dielectric thicknesses, which would in turn lead to incorrect measurements.

The second conclusion that can be made is that the ratio of **b/a** has to be approximately equal to or less than 1.5 when using seawater or distilled water as the dielectric. This requirement is necessary in order to produce a 10nF capacitor with a maximum 1m length copper pipe; thus resulting in a length that is easy and possible to work with. If the ratio is significantly less than 1.5, the resulting capacitance is greater than 10nF; therefore the length could be decreased accordingly to maintain the required total capacitance of 10nF. The length could not be decreased too much or else the resulting number of 5cm divisions would not be enough to allow for many measurements.

In order to verify the above conclusions, a plot of capacitance versus length was made for different ratios of **b/a**. The graphs depicted by figures 6 to 9 show the results using distilled water, seawater, oil, and air for five sample ratios. These ratios span the total available range of the copper pipe diameters available on the market.

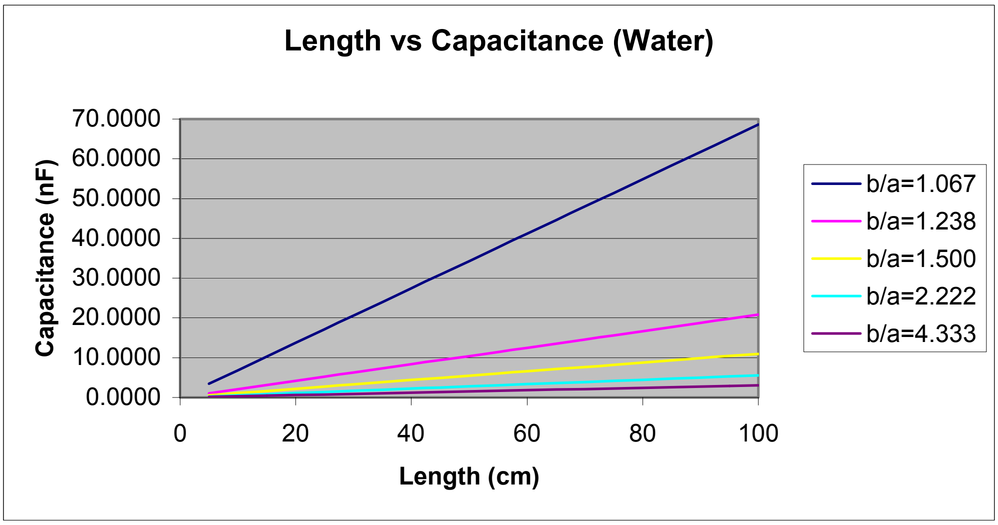

Figure 6

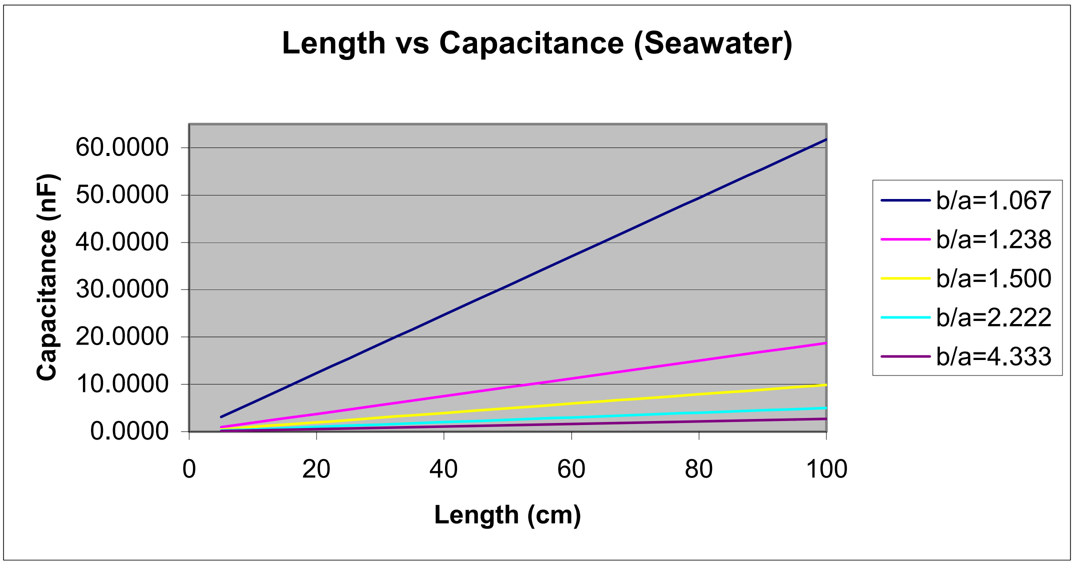

Figure 7

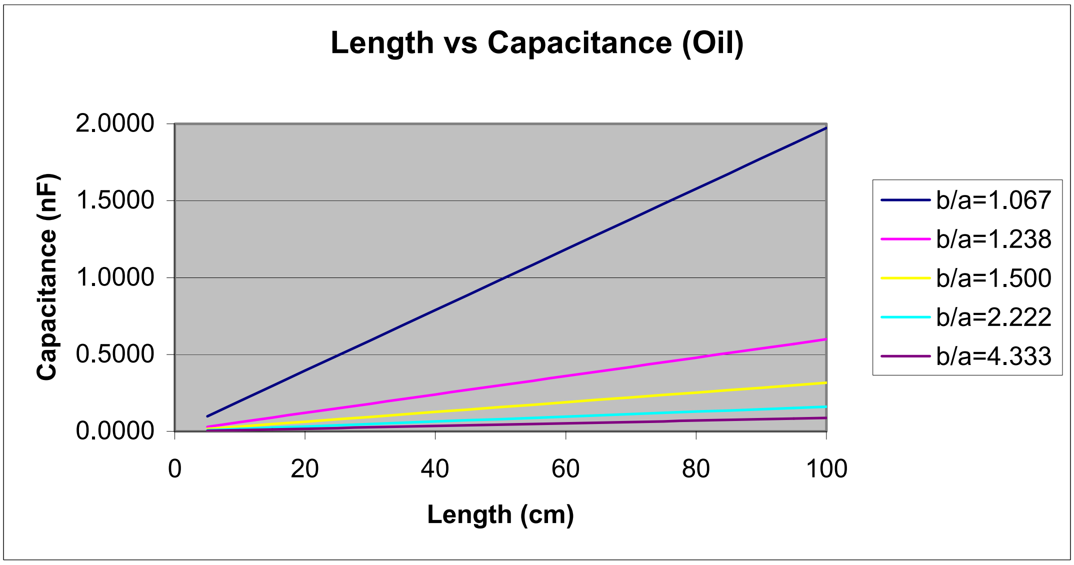

Figure 8

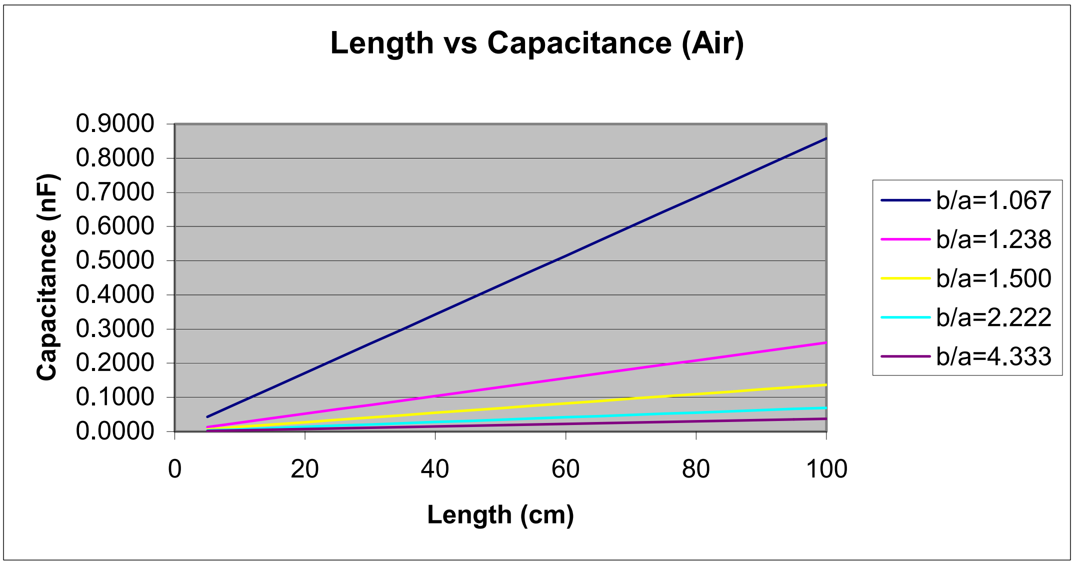

Figure 9

Based on all of the calculations above, there were 13 possible combinations of copper pipes that conformed to the restrictions that were placed. These are listed below along with the corresponding dielectric thickness:

Ø12 and Ø15 (1mm)
Ø12 and Ø18 (4mm)
Ø15 and Ø18 (1mm)
Ø15 and Ø22 (5mm)
Ø18 and Ø22 (2mm)
Ø18 and Ø28 (8mm)
Ø22 and Ø28 (4mm)
Ø22 and Ø35 (11mm)
Ø28 and Ø35 (5mm)
Ø28 and Ø42 (12mm)
Ø35 and Ø42 (5mm)
Ø35 and Ø54 (17mm)
Ø42 and Ø54 (10mm)

Table 3

The resulting dielectric thicknesses from the 13 possible combinations ranged from 1mm to 17mm. There were three combinations that resulted in a dielectric thickness of 5mm; Ø15/Ø22, Ø28/Ø35, and Ø35/Ø42. By selecting these three combinations, geometrical uniformity was ensured while the ratio of **b**/**a**, total length **L**, and the dielectric material with permittivity **ε**, could be experimented with.

The three combinations of copper pipes resulted in the following ratios of **b**/**a**: 1.333, 1.179, and 1.143. As the desired capacitance was approximately 10nF, the following copper pipe dimensions were required. Only distilled water and seawater are listed, as the restrictions placed could not be fulfilled with either air or water.

Inner Pipe (mm)		Outer Pipe (mm)			Distilled Water		Seawater	
Ø(a)	r(a)	Ø(b)	r(b)	b/a	L (cm)	C (nF)	L (cm)	C (nF)
15	7.5	20	10.0	1.333	65	10.05	72	10.02
28	14.0	33	16.5	1.179	37	10.02	41	9.99
35	17.5	40	20.0	1.143	30	9.99	34	10.19

Table 4

The dielectric thickness was 5mm for all three combinations. As 0.05cm<<30cm (the shortest length in the table), the fringing effect near the edges of the conductors could be ignored as it was negligible[7]. The final lengths of the copper pipes, based on table 4, were 75cm, 45cm, and 35cm respectively.

There is one remaining factor that must be calculated, and this is the total capacitance. Up until now, it has always assumed that the copper pipes were completely filled with the dielectric, whether it was air, oil, distilled water or seawater. If the copper pipes were not completely filled with a liquid, the remaining unfilled length would contain air, and this would result in two capacitors in parallel. One capacitor had the dielectric of the liquid and the second capacitor had the dielectric of air. As the two capacitors were connected in parallel, the equivalent capacitance was the sum of the individual capacitances. The level of the liquid

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[7] Field and Wave Electromagnetics

determined the capacitance of each capacitor as one had ***L=(liquid level)*** while the second one had ***L=(total length)-(liquid level)***. Plotting the length versus the total capacitance for each of the three ratios of **b**/**a** that were used yields the following graphs depicted by figures 10 and 11 for distilled water and seawater respectively:

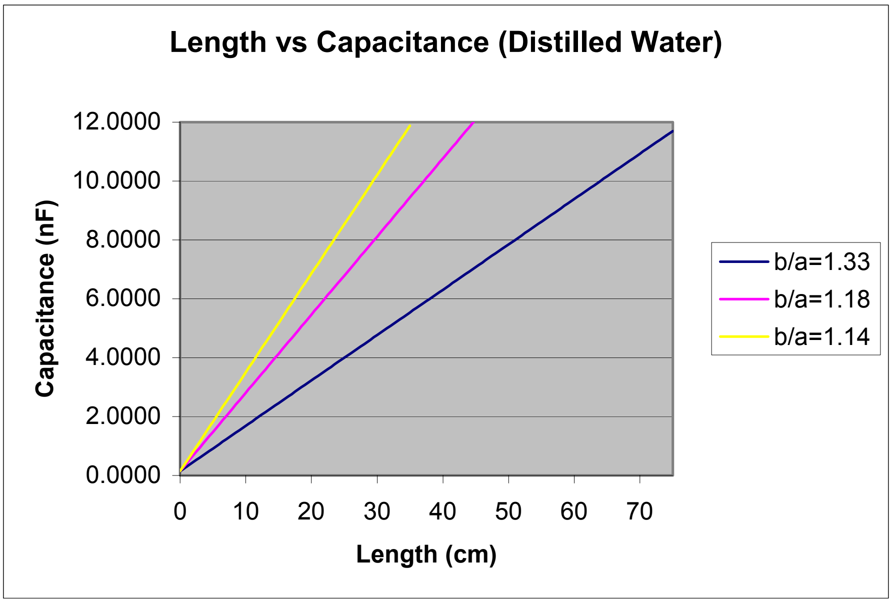

Figure 10

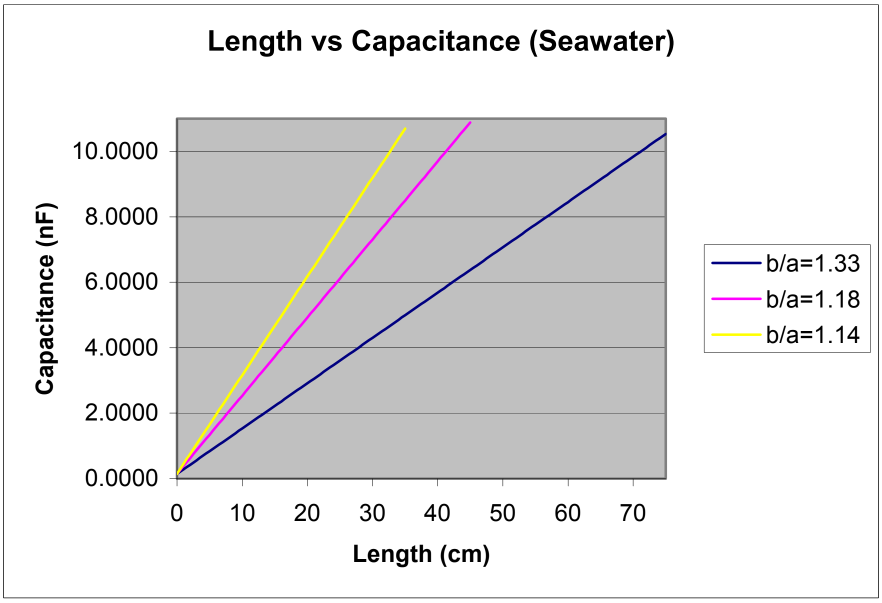

Figure 11

4. SWITCHING CIRCUITS

The principle on which the cylindrical capacitor operated is the following. The capacitor would be continuously charged and discharged. At a specific time interval, $\mathbf{t_1}$, the voltage across the capacitor would be measured. This voltage would be proportional to the capacitance of the capacitor and thus proportional to the level of the liquid that acted as the dielectric in the capacitor.

4.1 INITIAL MOSFET CIRCUIT

Initially, the circuit shown below was used for taking measurements. The capacitor (C) shown was the cylindrical capacitor that was constructed for this project. The resistor (R) was used to discharge the capacitor.

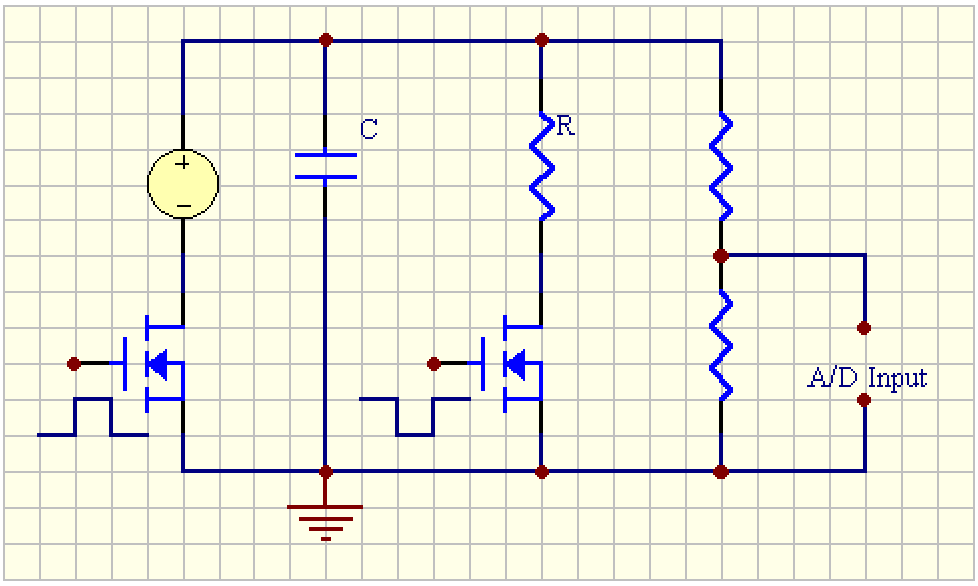

Figure 12

Two transistors, the IRF640 or IRF740 N-Channel enhancement mode MOSFETs, were used as switches. This switching was accomplished by supplying a voltage less than or greater than the gate threshold voltage of the transistor, $V_{GS(TH)}$. For both the IRF640 and IRF740, $V_{GS(TH)\ MIN}$=2V and $V_{GS(TH)\ MAX}$=4V. By applying less than 2V, the transistor operates in its cutoff state and therefore it is "OFF". By applying more than 4V, the transistor operates in its saturation region and it is "ON" [8]. As $V_{GS(TH)}$ ranges from 2V to 4V, standard TTL values can be used to control the transistors. Specifically, 0V were used for "OFF" and +5V were used for "ON".

It was determined that a high charging voltage would allow for better measurements as it would be easier to monitor the discharging of the capacitor. Due

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[8] Electrical Engineering: Concepts and Applications

to this, the initial capacitor voltage was set at approximately V_O=100V. Following the advice of the thesis advisor[9], it was decided to have a RC time constant of 10msec. Based on this, the corresponding value of the discharging resistor was 1MΩ. (1MΩ x 10nF = 0.01sec)

The two resistors to the far right of the diagram were used as a voltage divider. This was necessary as the input voltage range on the microcontroller is 0-5VDC while the capacitor would be charged to approximately 100V. The voltage divider consisted of two resistors, R_1 and R_2, as shown in figure 13:

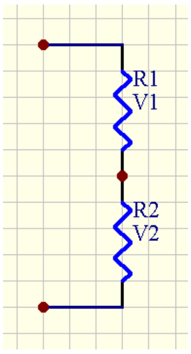

Figure 13

The following equations were used to calculate the values of R_1 and R_2.

$$V_{total} = V_1 + V_2 = 100V(approximately)$$

$$V_2 = 5V(Maximum\_Microcontroller\_Voltage)$$

$$V_1 = \frac{R_1}{R_1 + R_2} V \qquad V_2 = \frac{R_2}{R_1 + R_2} V$$

Before applying V_O=100V, it was decided to test the circuit and verify that the switching part of it worked properly and as expected. The test was done by applying V_O=3V using 2 "AA" batteries. Unfortunately the results were not the expected ones, as the switching did not work properly. According to the circuit, the voltage across the capacitor should have been equal to V_O during the charging period and it should have converged to 0V during the discharging period.

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[9] Mr. John Avaritsiotis

Measurements taken showed that the voltage across the capacitor was V_O=3V while the transistor was "ON" and charging and at a constant (V_O – 0.7V) = 2.3V during the "OFF" transistor state.

After closer investigation of the datasheets for the IRF640 and IRF740 transistors, it was determined that the diode incorporated in this semiconductor could be at fault. This diode can be seen in figure 14 as included in the transistor datasheet.

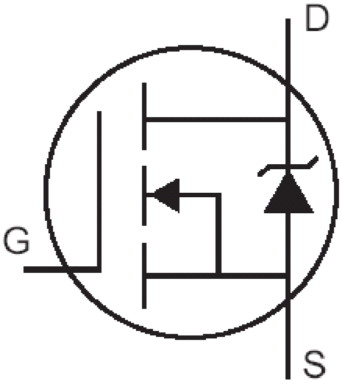

Figure 14

4.2 DARLINGTON TRANSISTOR CIRCUIT

As a second alternative, a NPN Darlington transistor, the BU323A, was substituted for the IRF640/IRF740. The revised circuit used can be seen below in figure 15:

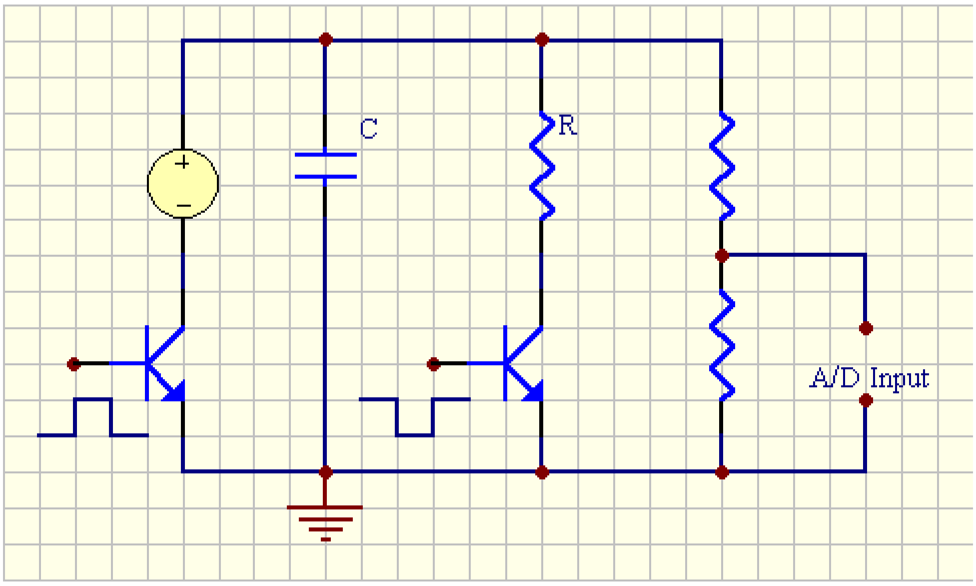

Figure 15

Regrettably, this transistor also produced similar results to the IRF640/IRF740, possibly because this transistor also contained an integrated diode, as can be seen in figure 16 from the datasheet. Another solution had to be investigated that overcame these switching problems.

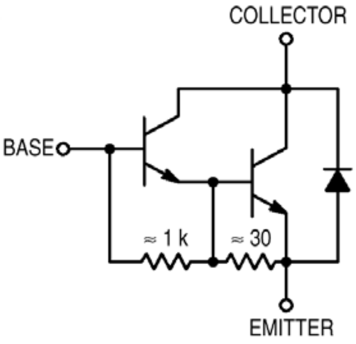

Figure 16

4.3 SOLID-STATE RELAY CIRCUIT

A decision was made to try and find a solid-state relay that could be used for the switching function of the circuit. A simple low voltage solid-state relay was found to verify that such a device would work properly in the circuit as it would switch approximately 3V instead of the 100V. The device selected was the EDR201A0500 relay. This relay produced the expected results as it switched the power to the capacitor properly but it could not handle the high DC voltage with which the capacitor was going to be charged. The circuit with this relay can be seen below in figure 17:

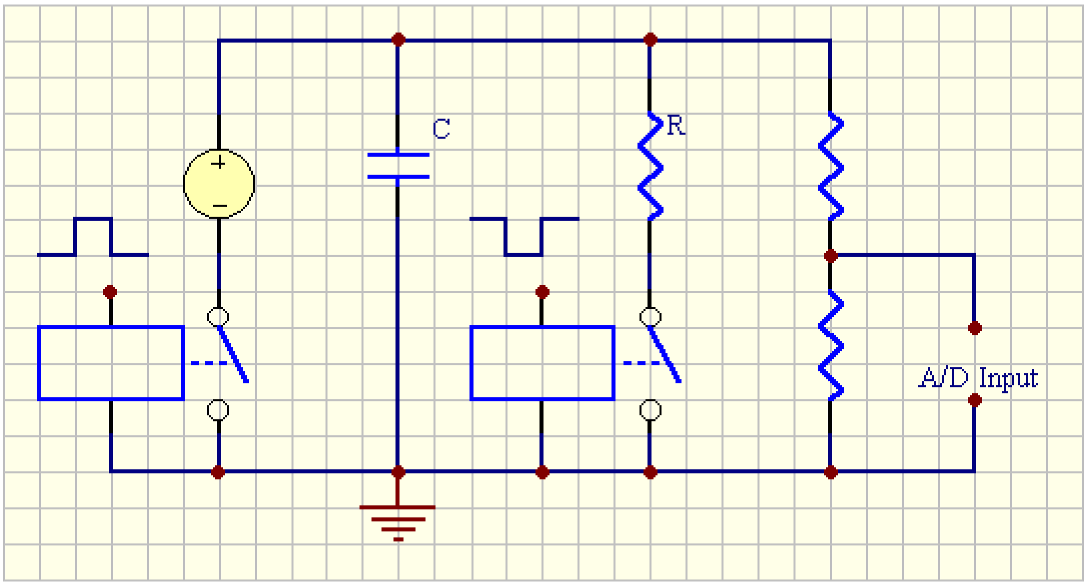

Figure 17

As the "test" solid state relay's operation was as expected, a final device would have to be found that would meet the following conditions: Ability to withstand at least 200VDC across the switching terminals, very fast switching times and switching operation with 0VDC and +5VDC. An extensive search on the Internet revealed many prospective candidates. These candidates were either solid-state relays or high voltage optocouplers.

Examples included the following:

- Siemens LH1056/LH1298/LH1540 High Voltage Solid State Relay Optocouplers
- Supertex HV214 250V Low Charge Injection 8-Channel High Voltage Analog Switch
- NAiS AQW210AH photoMOS Relay
- Crydom CMX200D3 Solid State Relay
- Fairchild HSR312/HSR412 Photovoltaic Solid-State Relay Optocouplers
- International Rectifier PVT412 Power MOSFET Photovoltaic Relay

Unfortunately none of these devices could be located in the local market and the lead-time for ordering most of them was extremely lengthy.

4.4 Final Transistor Switching Circuit

Following the advice of the thesis advisor[10], a fourth circuit was implemented to overcome all of the shortcomings of the previous 3 switching circuit attempts. The new circuit can be seen below in figure 18:

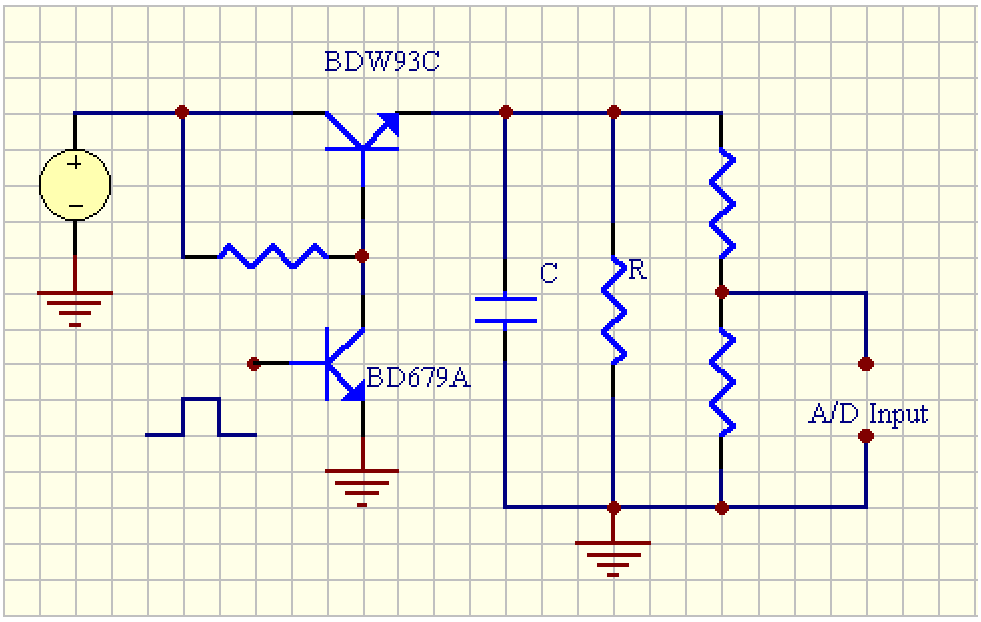

Figure 18

This new circuit required one pulse only, as opposed to two that were required by all of the previous circuits. When this pulse was "HIGH", (+5VDC) it turned "ON" the transistor, which in turn pulled the power resistor to ground. During this "ON" state all of the input current passed through the power resistor and the capacitor's charge was discharged through the discharging resistor (R). When the pulse was "LOW" (0VDC) the transistor was "OFF" and the input current charged the capacitor.

At this point, it should be noted that the charging voltage was reduced from approximately 130VDC to approximately 35VDC. This was necessary as the high voltage, in addition to several other factors, was causing electrolysis. The electrolysis phenomenon will be discussed further in section 8.3.

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[10] Mr. John Avaritsiotis

5. POWER SUPPLY CIRCUITS

Throughout the implementation of this thesis, several power supply circuits were required. As explained earlier, an initial condition for the capacitor's charging voltage was that it should be approximately 100VDC.

5.1 INITIAL CIRCUITS

Two methods of producing this voltage were analyzed. The first and easiest method was the use of batteries. By connecting ten 9V batteries in series, the resulting voltage was 99VDC, which fulfilled the approximate 100VDC criteria.

The battery power supply provided acceptable power for the purposes of this project. Unfortunately, due to the electrolysis issues that came up, the voltage fell to 75VDC in a short period of time. As a result, this method of supplying the necessary power was discarded.

The second power supply that was constructed utilized an AC power transformer. The following equations show the relationship between the AC line voltage of a transformer and the RMS voltage at the output. V_S is the transformer's secondary voltage and V_M is the maximum of V_S.[11]

$$
\begin{aligned}
V_{line} &= \sqrt{2}V_{rms}\sin\omega t \\
V_S &= V_M \sin\omega t \\
V_M &= N\sqrt{2}V_{rms}
\end{aligned}
$$

Solving for V_M = 100VAC, V_{rms} would have to be 70.7VAC, thus requiring a 220VAC to 71VAC transformer. This type of transformer was not readily available on the market and could only be obtained through a special order. This inherently would require a long lead-time and it would entail a high cost.

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[11] Electrical Engineering: Concepts and Applications

An alternative to this was to use a standard voltage transformer available on the market for adapting the local line voltage to appliances manufactured abroad. This is usually found in a 220VAC to 110VAC transformer. A multi-scale transformer was found that could transform the following voltages: 90V, 110V, 125V, 200V, 220V, and 240V. A picture of the transformer is shown below, along with a detailed picture of the input/output voltage selectors:

Figure 19

Figure 20

The line voltage was measured and was found to be 238.5VAC. Using the 240VAC to 90VAC step-down scale, with the given input line voltage, the output voltage was 89.4VAC. By using a full wave rectifier, and based on the formula listed previously, the final DC output voltage was 126.5VDC. The power supply circuit used is shown below in figure 21:

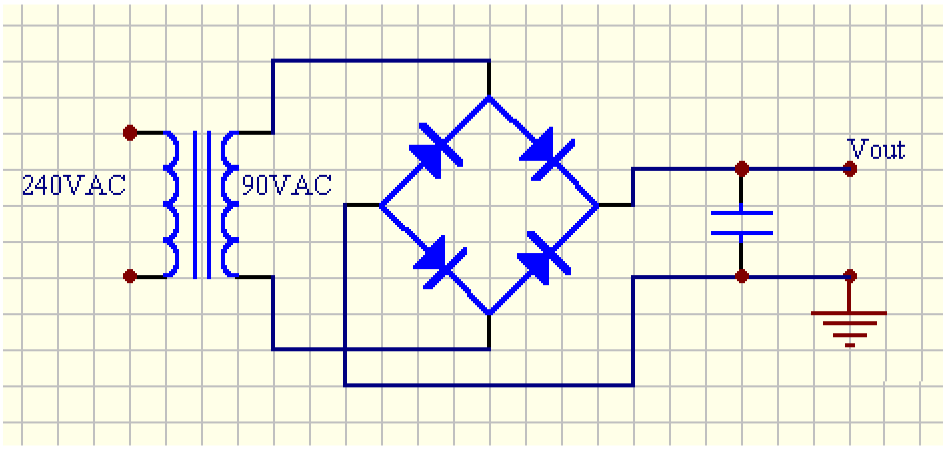


Figure 21

5.2 FINAL CIRCUIT

As mentioned earlier, the capacitor's charging voltage had to be reduced from approximately 130VDC to approximately 30VDC. The local market was investigated again and a survey was performed on the available step-down transformers. The largest standard transformer that was found was one that stepped down 220VAC to 24VAC.

Using the 220VAC to 24VAC ratio and the fact that V_{line} = 238.5VAC, it was calculated that V_{rms} = 26VAC. By using the equation for V_M listed above, it was calculated that V_M = 36.8VAC, and this was the voltage supplied to the capacitor in order to charge it. The complete final power supply circuit used is shown below in figure 22.A:

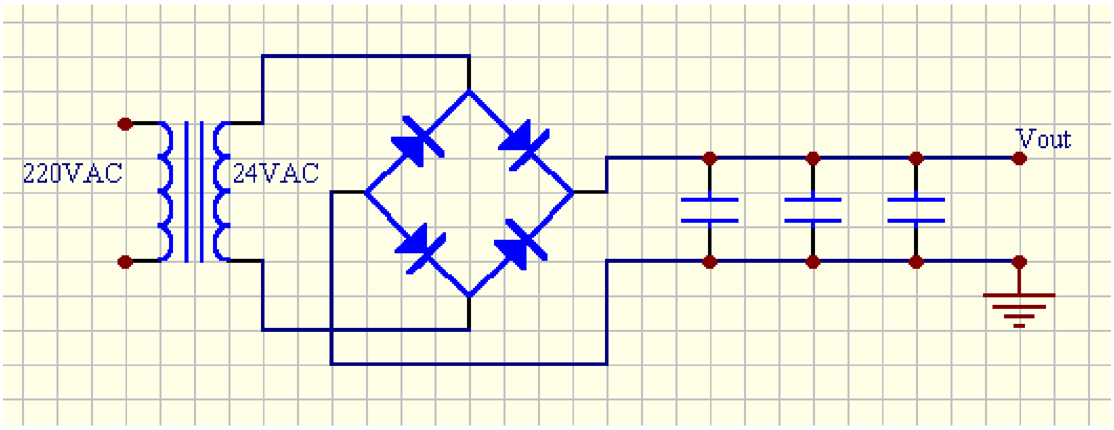


Figure 22.A

A picture of the final power supply circuit is shown below in figure 22.B.

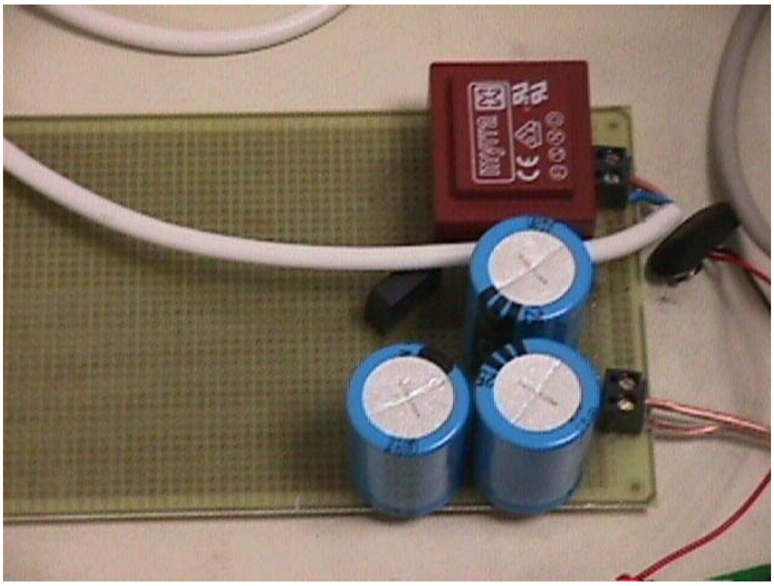
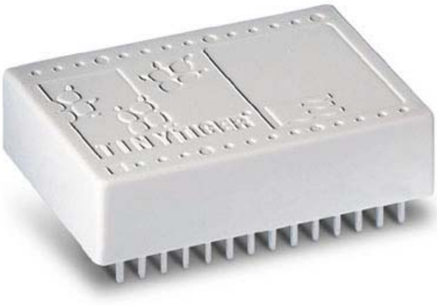


Figure 22.B

6. The Tiny Tiger Microcontroller

6.1 Introduction

The Tiny Tiger microcontroller is manufactured by Wilke Technology. Several models are available such as the BASIC Tiger, the Tiny Tiger and the Tiny Tiger Economy. For this project the Tiny Tiger Economy module was used along with the Tiny Tiger Prototyping Board. For the remainder of this paper, the Tiny Tiger Economy module will be referred to as the Tiger module for simplicity. The actual Tiger module is shown below with its pin-outs.



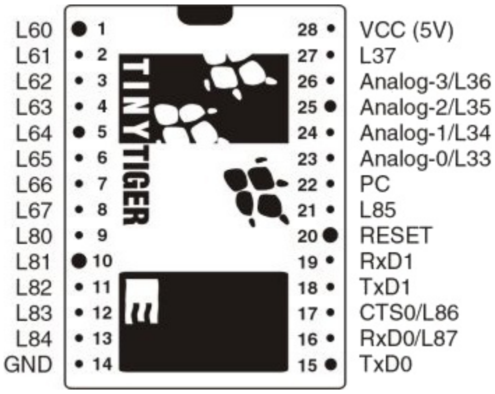


Figure 23 **Figure 24**

The basic features that differentiate the Tiny Tiger Economy microcontroller from the other two modules are the number of input/output ports, the on-board memory and the lack of an on-board real-time clock. This was acceptable for this project as the requirements of the microcontroller were quite simple: To generate a pulse for driving the switching circuit which in turn caused the capacitor to charge and discharge, and to take a voltage measurement during the capacitor discharging period at a precise interval t_m. As a 4-line by 20-character LCD module was also available for the Tiger module, this was used to display the voltage during the discharging period. This LCD module is shown below:

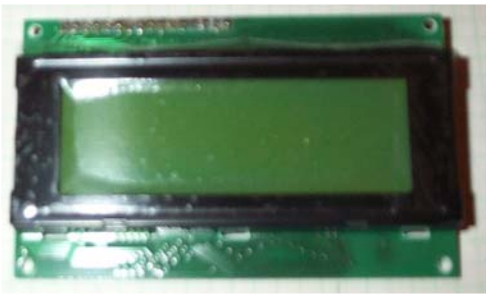


Figure 25

6.2 TIGER BASIC

The Tiger module was programmed with Tiny Tiger Basic, ver 4.01. Tiger Basic includes a modified BASIC instruction set that reduces the familiarization period for the programming of the module and makes this task very simple.

The Tiger module supports multitasking and can execute up to 32 tasks simultaneously. Approximately 10,000 to 100,000 BASIC instructions can be executed per second depending on the complexity of the instruction and the data volume. The memory capacity of the Tiger module is 32Kb. The BASIC program is compiled and downloaded to the Tiger module with the Tiger Basic development software suite.

6.3 PULSE GENERATION

The Tiger microcontroller can produce three ranges of frequencies using its base frequency and a division factor. The resulting frequency and time ranges that are possible are shown in the table below[12]:

Range	Range Frequency	Resolution	Time Range
1	2,500,000 Hz	0.400 µsec	0.0004 → 26.214 msec
2	625,000 Hz	1.600 µsec	0.0016 → 104.856 msec
3	156,250 Hz	6.400 µsec	0.0064 → 419.424 msec

Table 5

The Tiger microcontroller can produce a pulse using two different methods. The first method is by using the time-base timer device driver that is called "TIMERA". This device driver creates an internal adjustable time base that can be used by other device drivers. The TIMERA device driver is installed with two parameters, RANGE and DIVISION FACTOR and these parameters produce the time ranges listed in the table above. A table in the User's Manual[12] lists all of the possible division factors that can be used and the corresponding frequencies. A copy of these tables may be found in appendix C. To install the driver, the following syntax is used:

```
INSTALL_DEVICE #X, "TIMERA.TDD", Y, Z
```

---

[12] Basic Tiger Handbook, User Manual: Volume 2

This installs the TIMERA driver as device #**X** with the range parameter **Y** and a division factor of **Z**. Parameter **X** can range from 0 to 63 and parameter **Y** can be 1, 2, 3 or 0. If 0 is selected, the timer is stopped. A second device driver is required that will actually produce the pulse, and this is the PLS02 device driver. To install this driver the following syntax is used:

```
INSTALL_DEVICE #X, "PLS02_Pp.TDD"
```

This installs the PLS02 driver as device #**X** on pin **p** of port **P**. To generate the pulse, the following BASIC instruction is used with the syntax shown:

```
PUT #X, CNT, DUTY, CYCLE
```

This instruction will output **CNT** number of pulses to pin **p** of port **P**. The total time of the pulse will be **CYCLE** and the time that the pulse will be "HIGH" is equal to **DUTY**. Both **DUTY** and **CYCLE** can have a range of 0 to 65535. To produce 300 pulses on pin 0 of port 8 that are "HIGH" for 6msec and "LOW" for 4msec the following set of instructions would be required. Note that the installed time base is 10kHz.

```
INSTALL_DEVICE #2, "TIMERA.TDD", 1, 250
INSTALL_DEVICE #4, "PLS02_80.TDD"
PUT #4, 300, 60, 100
```

The second method of producing pulses with the Tiger module is by using the PLSOUT1 device driver. This device driver enables a very fast pulse output and can output pulses with high resolution, thus the advantage in using it. The drawback to this method is that the fast drivers utilize available hardware that cannot be shared; therefore it is not possible to simultaneously use another fast driver. To install this device driver the following syntax is used:

```
INSTALL_DEVICE #X, "PLSOUT1.TDD", AREA
```

This installs the PLSOUT1 driver as device #**X** and the parameter AREA determines the resolution of the driver. This parameter can be 1, 2 or 3 and these ranges correspond to the ones listed in table 5. The pulse output is always on pin 6 of port 8 and it cannot be changed. Similarly to the first pulse generation method, the **PUT** instruction is used to output the pulse but with the following difference; the **DUTY** parameter signifies the time for which the pulse is "LOW". To produce the same 300 pulses that are "HIGH" for 6msec and "LOW" for 4msec the following set of instructions would be required using this method.

```
INSTALL_DEVICE #3, "PLSOUT1.TDD", 2
PUT #3, 300, 2500, 6250
```

The output on pin 6 of port 8 is 300 pulses with a total time of 10msec (1.600μsec x 6250) of which 4msec (1.600μsec x 2500) are "LOW", thus the remaining 6msec are "HIGH".

6.4 A/D INPUT

The last function of the Tiger module that needs to be examined for the scope of this project is the analog to digital input. The voltage drop across the capacitor during its discharging period will be measured using this input method. There are several ways to acquire measurements from the A/D-Inputs on the Tiger module using the two available device drivers, ANALOG1 and ANALOG2. The basic difference between these two drivers is that ANALOG1 reads the instantaneous value of the analog input while ANALOG2 samples the input and stores the results in a first in, first out (FIFO) buffer. The ANALOG2 device driver also requires the TIMERA device driver in order to function, whereas the ANALOG1 does not. Using the ANALOG1 driver, 8-bit and 10-bit resolutions are supported, while using the ANALOG2 driver, 8-bit, 10-bit and 12-bit-interpolated resolutions are supported. The following syntax is used to install the ANALOG1 driver:

```
INSTALL_DEVICE #X, "ANALOG1.TDD"
```

The instantaneous inputs are then read with the GET command. Various ways of reading the A/D inputs are possible depending on the syntax of the GET command that is used, as shown below:

```
GET #X, #0, 1, VALUE   (Reads 8-bit value from channel 0)
GET #X, #3, 2, VALUE   (Reads 10-bit value from channel 4)
GET #X, #4, 4, VALUE   (Reads 8-bit value from channels 0,1,2,3)
GET #X, #5, 8, W$      (Reads 10-bit values from channels 0,1,2,3
                        into a string that should be 4 x 2 bytes)
```

The following example shows how to install and use the ANALOG1 device driver so that it reads the input from A/D channel 0 in a 10-bit format:

```
INSTALL_DEVICE #6, "ANALOG1.TDD"
GET #6, #0, 2, ATOD
```

The ANALOG2 device driver is installed in the same way as the ANALOG1 driver. A prerequisite is the installation of the TIMERA device driver prior to that of the ANALOG2 device driver. The ANALOG2 device driver has several user function codes that set the necessary parameters required for the device driver to function properly and as required by the user. Due to this, the file "UFUNC3.INC" must be included in the program so that the compiler can recognize the symbol names used.

The following table from the user's manual[13] lists the parameters available that can be set using the PUT command:

Parameter Name	**Description**
UFCO_AD2_CHAN	Set single channel mode. → *0, 1, 2, or 3*
UFCO_AD2_RESO	Set resolution → *8=8=bit, 10=10-bit, 12=12-bit*
UFCO_AD2_INTEG	Integration width at 12-bit. → *16, 32, 64, or 128*
UFCO_AD2_STOVL	Flag: Stop on FIFO Overflow → 0=yes, n=no=wrap-around
UFCO_AD2_ANZ	No. of measurements per channel → 0=endless (FIFO), n=no of measurements (LONG)
UFCO_AD2_PSCAL	Pre-scaler, that divides the reference frequency of TIMERA. → 0,1=no pre-scaler, n=divider
UFCO_AD2_STOP	Stop A/D sampling
UFCO_AD2_GROF	Set string size adjustment flag → 0=spontaneous assignment at end of measurement, else=dynamic adjustment during measurement
UFCO_AD2_SCAN	Set multiple channels mode and number of channels used → n=1, channel used by UFCO_AD2_CHAN, n=2:2-channels (Ch-0, Ch-1), n=3:3-channels (Ch-0, Ch-1, Ch-2), n=4:4-channels (Ch-0, Ch-1, Ch-2, Ch-3)
UFCO_AD2_ISAMP	Integrate samples: Determines that every nth measurement will be written to the buffer, only for 12-bit resolution
UFCO_AD2_PSCIMM	Set pre-scaler immediately, (without a restart)

Table 6

The ANALOG1 device driver was used in this project, as an instantaneous measurement was required after each pulse. For academic purposes, a sample program that uses the ANALOG2 device driver can be found in Appendix B. This program was written for experimental reasons in order to determine which method of measurements was most suitable for this thesis project.

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[13] Basic Tiger Handbook, User Manual: Volume 2

7. PULSE GENERATION

Even though the Tiger module is perfectly capable of producing the necessary pulses to drive the switching circuit that would charge and discharge the capacitor, a second alternative was used initially to examine and analyze the behavior of the capacitor. The second alternative consisted of the 555-timer in an astable operation mode. Recompiling, download the program and restarting the Tiger module required a few minutes therefore this second alternative was chosen as the pulse frequency was easily varied by using a potentiometer with the 555-timer rather than reprogramming the Tiger module.

7.1 USING THE 555-TIMER

The 555-timer is a highly stable controller capable of producing accurate oscillation[14] (astable operation) by using two resistors and one capacitor, all of which are external components. The 555-timer can also be used for monostable operation but this mode of operation will not be discussed, as it is not applicable to this project. The typical circuit for astable operation is the following, as shown from the datasheet[14]:

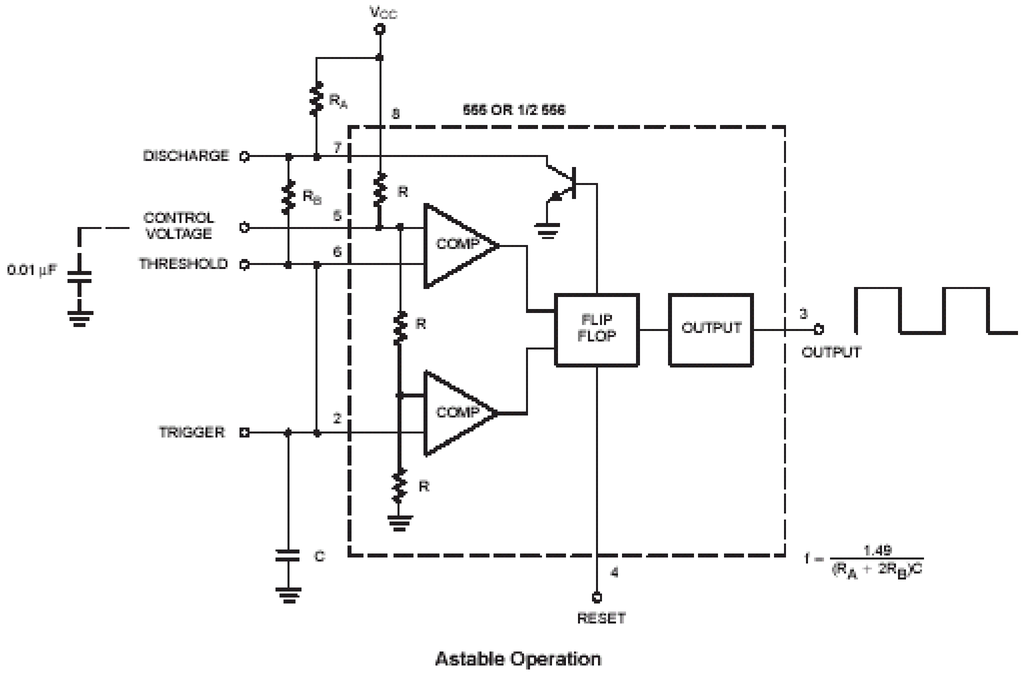

Figure 26

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[14] NE/SA/SE555/SE555C Datasheet, Philips Semiconductors

This circuit produces a square wave pulse output whose HIGH-level duration is $\mathbf{t_H}$ and LOW-level duration is $\mathbf{t_L}$. The respective high and low level durations can be calculated using the following equations[15]:

$$t_H = 0.693(R_A + R_B)C$$
$$t_L = 0.693(R_B)C$$

Using the above equations with the following component values resulted in these final high and low level durations: $\mathbf{t_L}$ = 25.6msec and $\mathbf{t_H}$ = 25.6 → 25.8msec:

C = 10nF

R_A = 22KΩ Potentiometer

R_B = 3.7MΩ

These times were selected as such, since they were approximately 2½ times the RC constant (10msec) of the capacitor under analysis (10nF) and the discharging resistor (1MΩ). This allowed ample time for charging the capacitor and provided an adequate settling period after the capacitor has discharged. As the switching circuit described in figure 18 from section 4.4 resulted in the capacitor's discharge during the pulse's high-level output, having $\mathbf{t_H} > \mathbf{t_L}$ ensured that the discharging time would be greater than the charging time.

Taking the component values that were calculated into account, the final 555-timer circuit that was used for the initial measurements is the following:

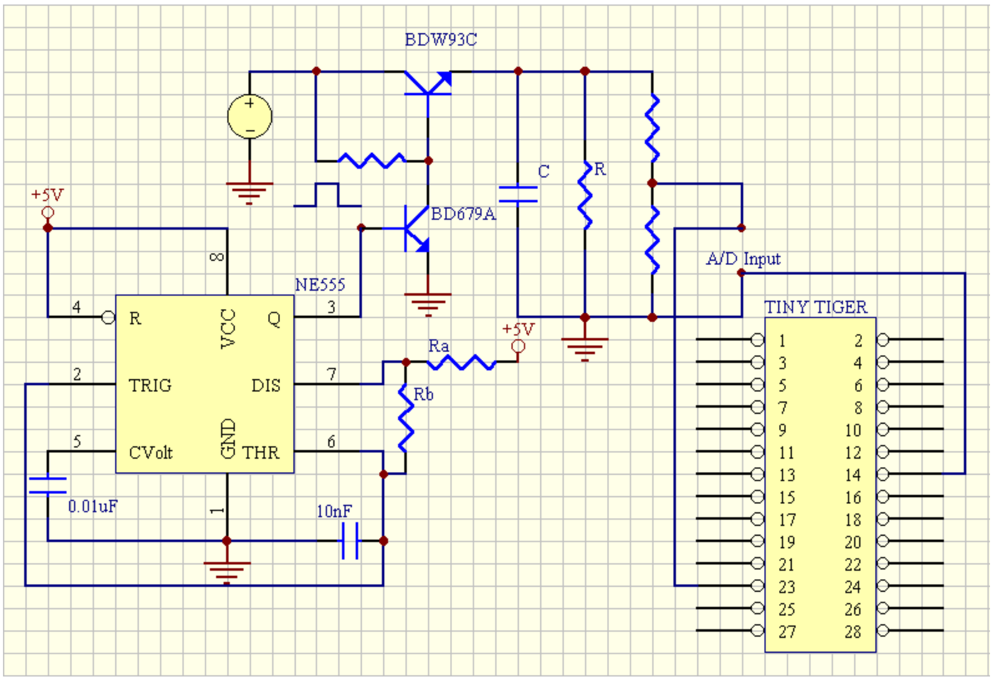

Figure 27

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[15] NE555, SA555, SE555 Precision Timers Datasheet, Texas Instruments

7.2 USING THE TINY TIGER MICROCONTROLLER

Using the Tiger module to produce a pulse was a relatively easy task, as described in section 6.3. The corresponding t_H and t_L times were set via software. The final Tiger module circuit that was used is the following:

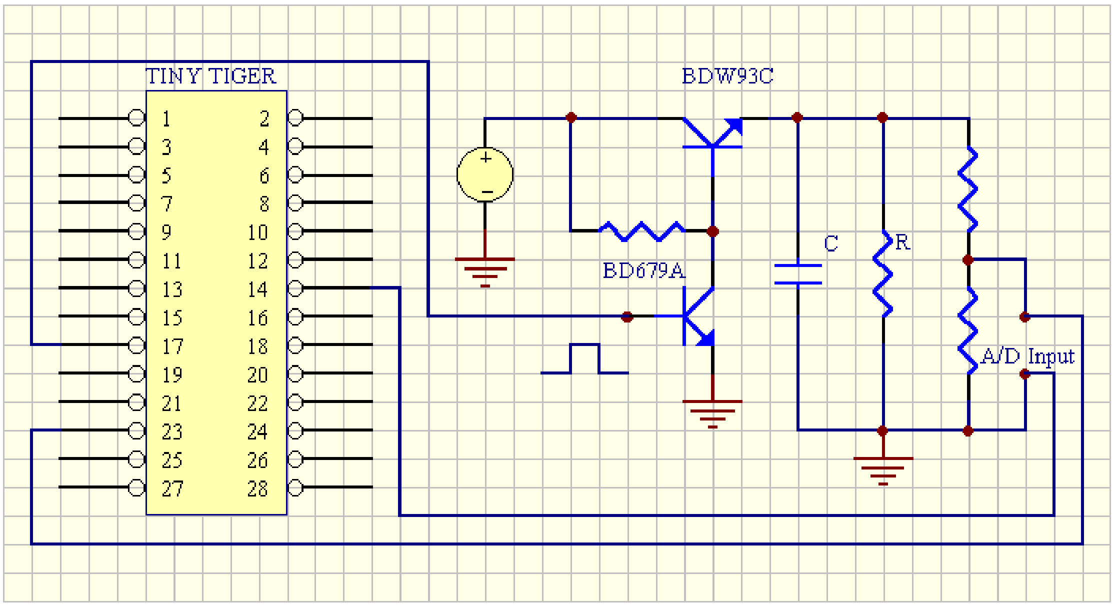

Figure 28

8. CONSTRUCTION DETAILS

8.1 CAPACITOR CONSTRUCTION

Recalling from section 3, there were three possible combinations of copper pipes that could be used to construct a capacitor the met the restrictions placed. Two of these three possible capacitors were constructed, the 75cm and the 45cm ones. The inner copper pipe was left 3cm longer than the outer copper pipe in order to be able to solder the leading cables without creating any short circuits and to facilitate the alignment of the two copper pipes. The two copper pipes that made up the capacitor were placed concentrically and were kept centered with a rubber washer. This rubber washer was pushed in approximately 2mm from the edge of the copper pipes and the resulting gap was filled with an epoxy-like compound that hardened and kept the copper pipes stable. The details of the copper pipe ends can be seen in the following pictures:

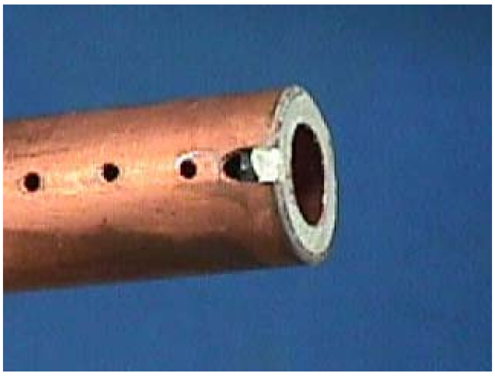

Figure 29

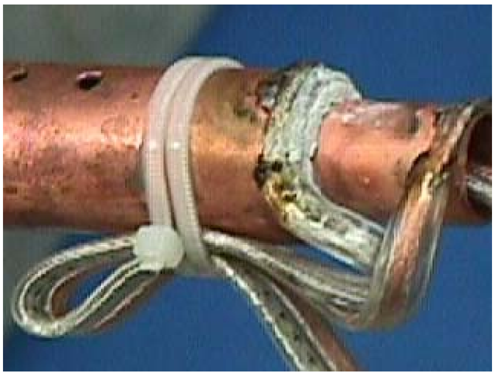

Figure 30

The outer copper pipe was drilled every 1cm so that the dielectric could enter the two pipes and fill the gap in between them. This was necessary as the ends of the copper pipe were sealed. An early thought was to leave some holes in the ends of these washers so that the liquid could enter the tubes. This idea was discarded, as the holes would compromise the alignment of the two copper pipes. A detail of the holes that were made can be seen in the picture below, noting that the larger holes represent the 5cm divisions:

Figure 31

8.2 Holding Tank Construction

A 75mm diameter plastic pipe was used as a holding tank to house the liquids that would act as the capacitor's dielectric. The construction details of this plastic pipe can be seen in the picture below:

Figure 32

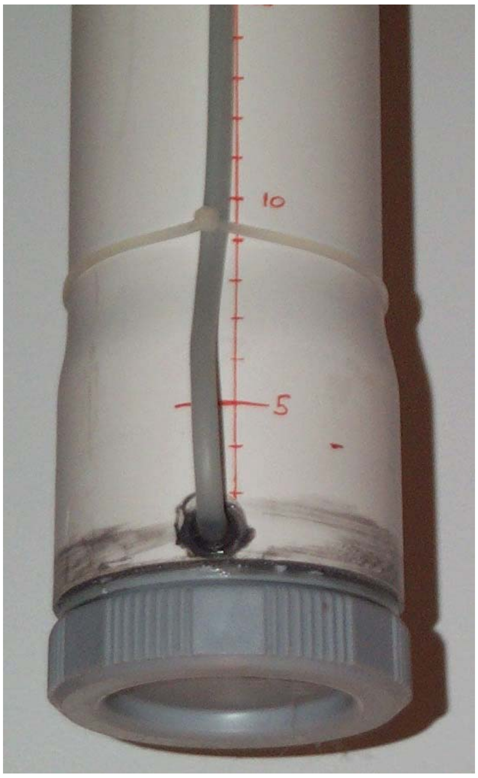

Figure 33

The small exterior transparent tube was used to view the level of the liquid inside the plastic pipe.

8.3 Electrolysis and Corrective Measures

The problem of electrolysis was encountered early during the initial measurement periods. This was a reason for redesigning half of the project, primarily the power supply circuit and the construction of the capacitor. The electrolysis problem was partially solved with the aid of a clear varnish spray. One of the capacitors constructed, specifically the 45cm one, was taken apart and coated with a film of varnish on all 3 of the copper pipe surfaces, excluding the inner surface of the inner copper pipe. This capacitor was selected for the modifications as it was made of copper pipes that were shorter in length and larger in diameter than the 75cm capacitor, thus making it easier to coat the interior copper pipe surface.

Special care was taken to ensure that the varnish was applied as uniformly as possible. Coating the entire inside surface of the outer copper pipe proved to be difficult as the overall length of the copper pipe was 45cm and the spray did not reach the center of the pipe easily. The inner surface of the inner copper pipe was not coated as the critical surfaces were the ones between the two copper pipes, specifically the outer surface of the inner pipe and the inner surface of the outer pipe. The varnish was allowed to dry over night and the capacitor was reassembled the next day.

The modified capacitor, along with the new power supply circuit, was successfully tested with the lowered voltage and the problem of electrolysis had been solved, at least for the most part. The solution was a partial remedy as some very minor electrolysis was still evident due to the fact that the varnish had not uniformly coated the copper pipe surfaces. This electrolysis was still evident as some green residue was visible in the holding tank's water after period of time had elapsed while taking measurements.

This layer of varnish surely altered the total capacitance of the capacitor. Determining the magnitude of this change was not pursued as the effect was assumed to be minimal. This is due to the thickness of the varnish coating being very small and the fact that varnish is an insulator thus the dielectric constant is insignificant compared to the dielectric constant of water. To illustrate the insignificance of the varnish, the following example can be used: Assume that the insulation thickness of a flat 2-conductor antenna cable is altered. If the distance between the two conductors is not changed, the effect on the capacitance will be insignificant.[16]

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[16] Field and Wave Electromagnetics

9. MEASUREMENTS AND RESULTS

9.1 INITIAL CAPACITOR RESPONSE MEASUREMENTS

A variety of measurements for each capacitor were made in the lab that yielded some very interesting results. Initial microcontroller A/D measurements were not usable, as the results did not show anything but zero values, mostly due to the electrolysis that was observed. An oscilloscope was then used to troubleshoot the behavior of the capacitor. With the help of the thesis advisor,[17] and a colleague from the lab who had built a similar 555-timer pulse circuit, the response of the capacitor was examined. The results are shown in the picture below:

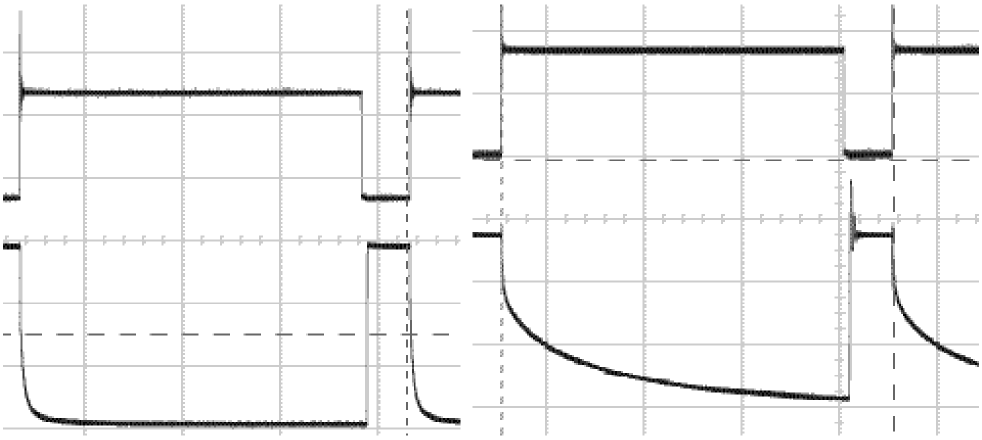

Figure 34

The waveform on the left shows the 555-timer pulse and voltage across the 45cm capacitor as it discharges, without any water. The charging voltage applied to the capacitor was 30VDC. The waveform on the right was obtained when the capacitor was completely filled with distilled water. The 45cm capacitor had been coated with the coat of varnish when these measurements were made.

Comparing the above waveforms with the theoretical waveforms from section 2, one can see that the capacitor exhibits the expected results as the voltage across the capacitor exhibits an exponential decay. As the capacitance increases, due to an increase of the dielectric between the two pipes, the capacitor takes longer to discharge. The waveforms shown above depict the two extreme conditions of the dielectric's height; without any water and completely filled with water. Measurements were also taken at 10cm intervals and these can be found in appendix A.

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[17] Mr. John Avaritsiotis

9.2 Tiny Tiger Measurements

The second set of measurements taken was with the Tiger module. The Tiger module was used to produce the pulse output and the total pulse cycle was 6.4msec, with a 3.2msec high-level followed by a 3.2msec low level. This translates to a pulse frequency of 156.25Hz. Measurements were made at every 5cm divisions of water. The resulting combined oscilloscope output is shown below.

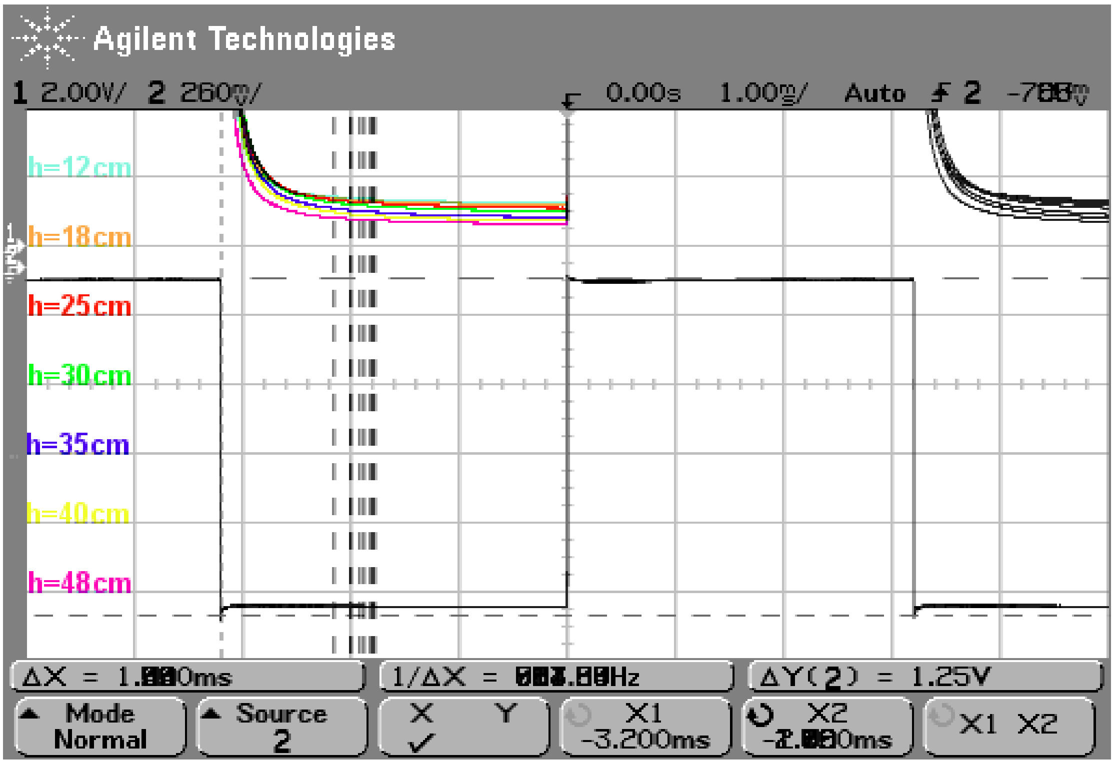

Figure 35

The waveforms shown are not in line with the expected results for the following reasons. (Individual waveforms can be found in appendix A.) In fact, the results obtained are the exact opposite of the theoretical results. As one can see from the above waveforms, the capacitor discharges in a shorter period of time as the water level increases, incorrectly indicating that the capacitance is decreasing. A second irregularity is that the discharging of the capacitor appears to happen while the microcontroller pulse is low. This is also not in line with the expect results as the circuit used charges the capacitor while the pulse is low and discharges it while the pulse is high. These results may be the result of either one of the following: incorrect oscilloscope probe placement on the circuit or unexpected circuit behavior due to the low frequency pulse that was used as the capacitor did not have enough time to charge and discharge completely.

Unfortunately, no additional measurements are available from the Tiger module. During the measurements phase, a resistor’s connections from the A/D voltage divider were accidentally shorted and 40VDC were applied to the Tiger module’s A/D input. This high voltage ruined the Tiger module, as the maximum A/D voltage input allowed is 5VDC. This Tiger module was obtained through a special order from abroad and ordering a replacement module in a timely fashion that would allow further measurements was not feasible.

9.3 Final 555-Timer Measurements

Additional measurements were also made with the oscilloscope using the 555-timer circuit. The resistor values for R_A and R_B that were originally calculated in section 7.1 did not produce any useable results. One reason was that the potentiometer was not sensitive enough to lock onto a specific value. The resulting waveforms contained too much distortion and the oscilloscope's trigger couldn't work properly. This problem was overcome by using a 12KΩ precision trimmer that was available in the lab. R_B was replaced with a 1.1KΩ resistor instead of the 3.7MΩ resistor, based on the following graph from the datasheets[18]:

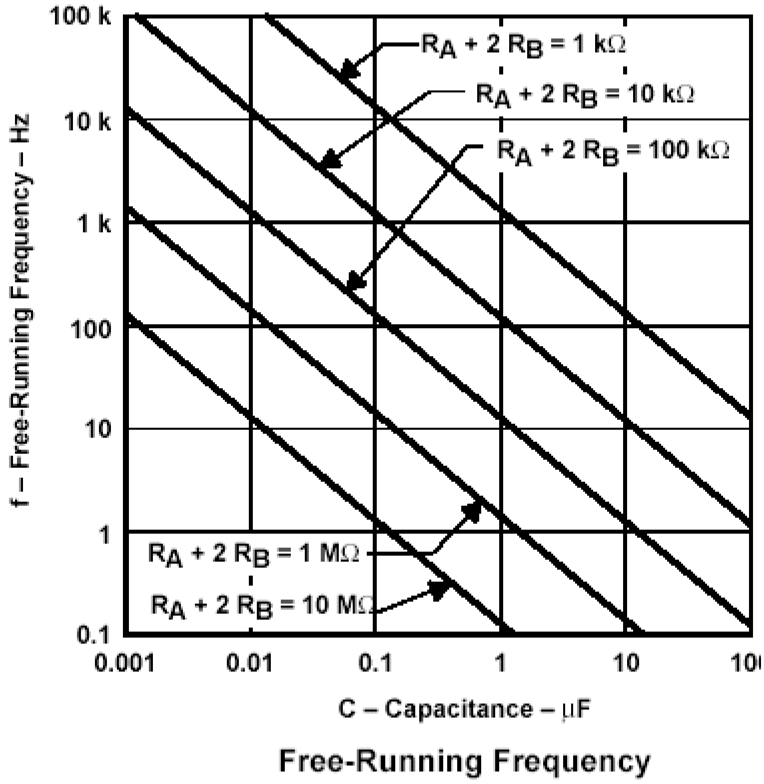

Figure 36

These values result in a frequency range of approximately 10kHz to 100kHz, a range that is higher than the one used for the initial capacitor response measurements which was 5kHz.

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[18] NE555, SA555, SE555 Precision Timers Datasheet, Texas Instruments

The resulting measurements from the capacitor were exactly as expected and in accordance with the theoretical results. The combined graph of the 45cm capacitor discharging with water at every 5cm interval can be seen below:

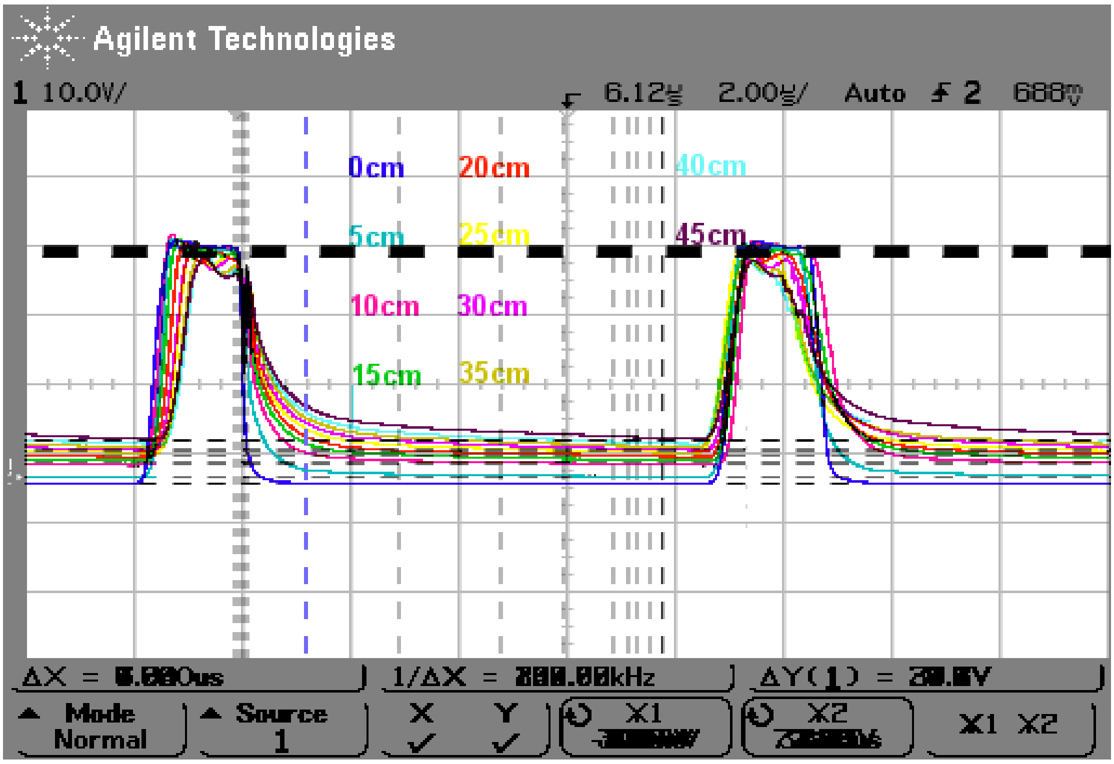


Figure 37

The pulse frequency is approximately 90kHz and an adequate settling period can be observed on the graph. Based on that fact that each major division is 2µsec, one can see that the microcontroller would have to take an A/D measurement 1.2µsec after the pulse generated initially goes into a HIGH state. Individual graphs for each 5cm interval can be found in appendix A.

By taking a measurement at 1.2μsec after the capacitor starts discharging, the behavior of the sensor can be examined. This particular measuring point can be seen in figure 37, depicted by the blue vertical dashed line. The relationship between the height of the liquid and the voltage across the capacitor can be seen in the graph below depicted by figure 38.

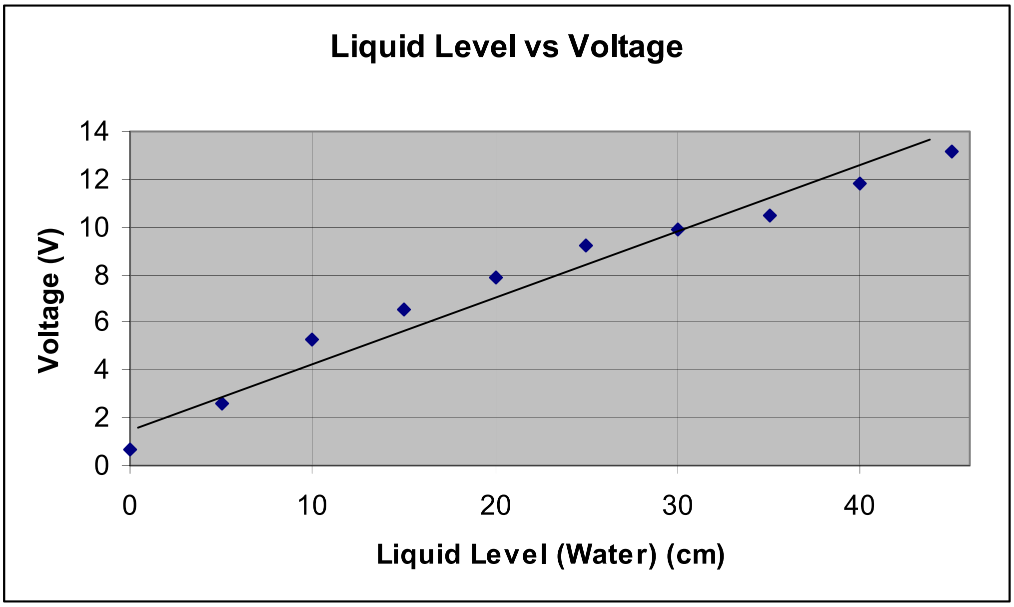


Figure 38

The individual measurements taken from the capacitor can be seen in the graph and a best-fit line has also been inserted. Several of the points exhibit a deviation from the best-fit line and this is expected as the cause can be experimental error and/or deviations caused by the electrolysis. The best-fit line shows that the sensor exhibits a linear response and discreteness in the measurements as each height has only one corresponding voltage. The relationship between the height of the liquid and the voltage can be depicted by the following equation, which results from the slope and y-intercept of the best-fit line:

$$V = 0.275h + 1.5$$

The sensitivity of the sensor cannot be extracted from this graph. To measure the sensitivity, one would have to gradually increase the height of the liquid while observing the point at which the voltage would change. A sensor with a high sensitivity would exhibit a change in voltage with a few millimeters of liquid while a low sensitivity sensor would require several centimeters of liquid before showing a change in the voltage. As the microcontroller was damaged, it was not possible to take these sensitivity measurements.

Lastly, the 75cm capacitor that was not coated with a coat of varnish was also measured for comparison reasons. Looking at the graph below, it is obvious that no measurements can be taken to distinguish the height of the liquid. The results are most likely due to the fact that electrolysis is taking place and therefore the capacitor is not exhibiting the characteristics of a capacitor.

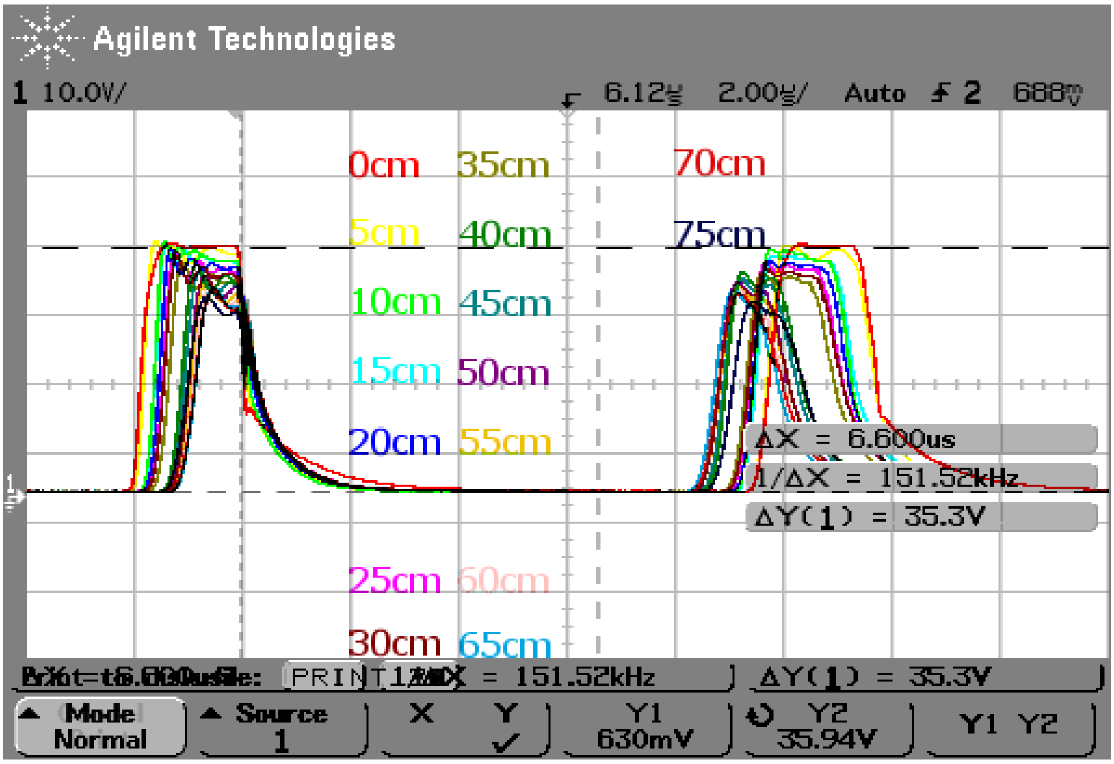
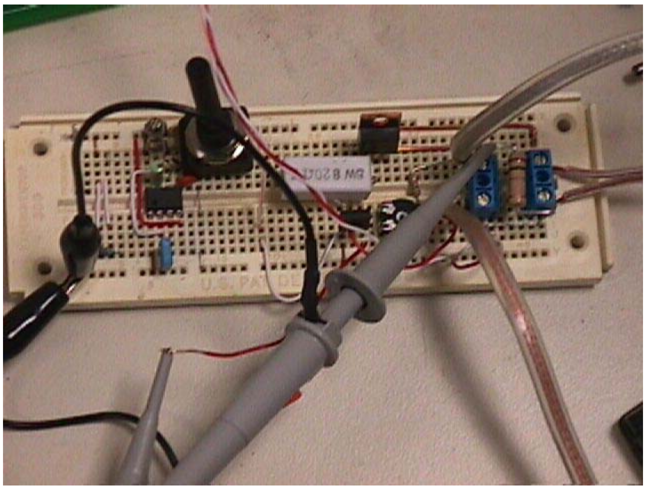


Figure 39

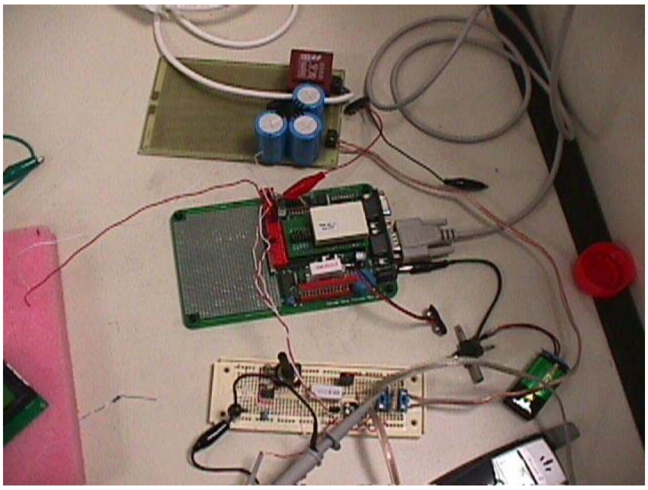
Only the 0cm and 75cm individual graphs are included in appendix A for reference. Inclusion of the remaining ones is deemed unnecessary.

Several photographs taken during the measurements are included below:

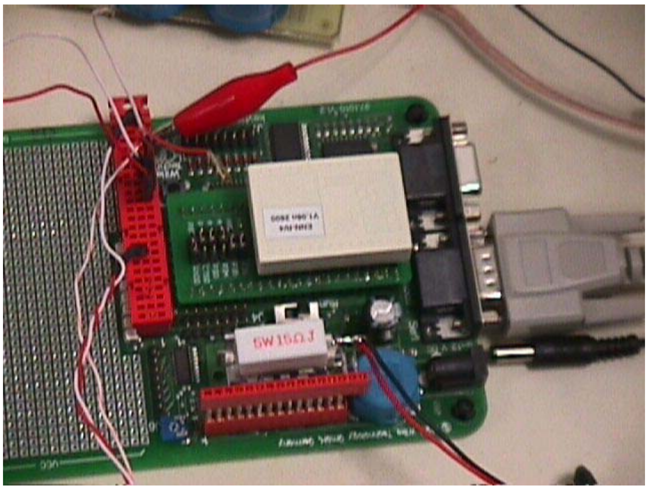


This photograph shows the breadboard and oscilloscope probe.

The Tiger module is being used to produce the pulses driving the transistors.



This photograph shows the overall power supply, Tiger module and breadboard interconnections.



A close-up photograph of the Tiger module without the LCD display module.

A photograph of the copper pipes inside the holding tank.

9.4 Precision Component Tester Measurements

The final measurements that were collected dealt with the capacitor itself. A precision component tester was available in the lab and three types of measurements were made for the capacitor at 5cm intervals of dielectric liquid for the 45cm capacitor. These measurements were the total capacitance, and AC impedance that consists of the resistance and the impedance angle of the capacitor. Under ideal conditions, a capacitor will have zero resistance and an impedance angle of –90°. (Similarly, an ideal inductor will have zero resistance and an impedance angle of +90°.) A resistor does not have an impedance angle, as it is not an energy-storage element[19]. The measurements taken are listed in the table below.

	10kHz	**20kHz**	**40kHz**	**100kHz**	**200kHz**	**400kHz**	**1MHz**
0cm	1.4 nF 5300 Ω -26.9 °	0.95 nF 4200 Ω -30.0 °	0.65 nF 3300 Ω -32.2 °	0.41 nF 2400 Ω -38.1 °	0.33 nF 1800 Ω -47.8 °	0.29 nF 1200 Ω -61.0 °	0.28 nF 600 Ω -74.8 °
10cm	16.3 nF 387 Ω -23.7 °	9.90 nF 314 Ω -23.1 °	5.68 nF 268 Ω -22.6 °	3.41 nF 227 Ω -29.1 °	2.92 nF 183 Ω -42.0 °	3.94 nF 122 Ω -58.3 °	3.24 nF 51 Ω -73.4 °
15cm	25.5 nF 267 Ω -25.4 °	15.3 nF 214 Ω -24.4 °	8.74 nF 182 Ω -23.6 °	5.13 nF 152 Ω -29.3 °	4.31 nF 122 Ω -41.5 °	5.77 nF 82 Ω -57.4 °	5.09 nF 33 Ω -71.9 °
20cm	34.8 nF 211 Ω -27.5 °	20.8 nF 167 Ω -26.0 °	67.3 nF 141 Ω -24.7 °	6.7 nF 118 Ω -29.8 °	5.6 nF 95 Ω -41.6 °	7.5 nF 63 Ω -57.3 °	7.0 nF 24 Ω -70.9 °
25cm	42.2 nF 187 Ω -29.9 °	24.1 nF 148 Ω -26.8 °	74.6 nF 126 Ω -24.9 °	7.8 nF 107 Ω -31.4 °	6.7 nF 84 Ω -45.0 °	8.6 nF 53 Ω -60.7 °	8.97 nF 19 Ω -72.4 °
30cm	52.6 nF 162 Ω -32.4 °	30.2 nF 126 Ω -28.6 °	86.1 nF 106 Ω -25.7 °	9.2 nF 89 Ω -31.1 °	7.8 nF 71 Ω -44.3 °	10.21 nF 45 Ω -59.9 °	11.1 nF 15 Ω -70.9 °
35cm	62.3 nF 148 Ω -35.3 °	36.6 nF 112 Ω -31.0 °	92.3 nF 93 Ω -27.6 °	11.0 nF 77 Ω -32.3 °	9.3 nF 61 Ω -44.9 °	12.0 nF 38 Ω -60.2 °	14.0 nF 12 Ω -69.8 °
40cm	71.9 nF 134 Ω -37.2 °	43.1 nF 100 Ω -32.8 °	100.4 nF 82 Ω -28.9 °	12.9 nF 67 Ω -33.1 °	10.8 nF 53 Ω -45.5 °	14.0 nF 33 Ω -60.4 °	17.9 nF 10 Ω -68.2 °
46cm	79.2 nF 126 Ω -38.0 °	46.8 nF 94 Ω -33.5 °	105.9 nF 76 Ω -29.5 °	13.9 nF 63 Ω -33.2 °	11.6 nF 49 Ω -45.3 °	15.1 nF 30 Ω -60.1 °	19.9 nF 9 Ω -67.1 °

Table 7

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[19] Electrical Engineering: Concepts and Applications

Plotting the capacitance values for each frequency and height of water yields the following graph:

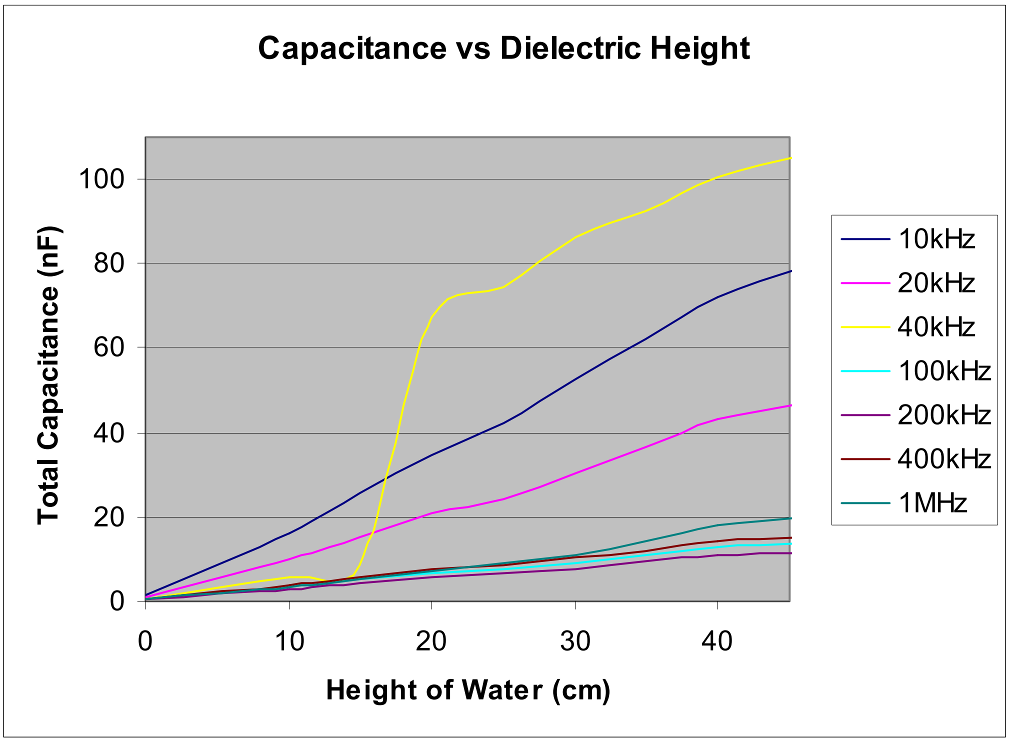

Figure 40

The same data can be plotted in a three dimensional graph as shown below:

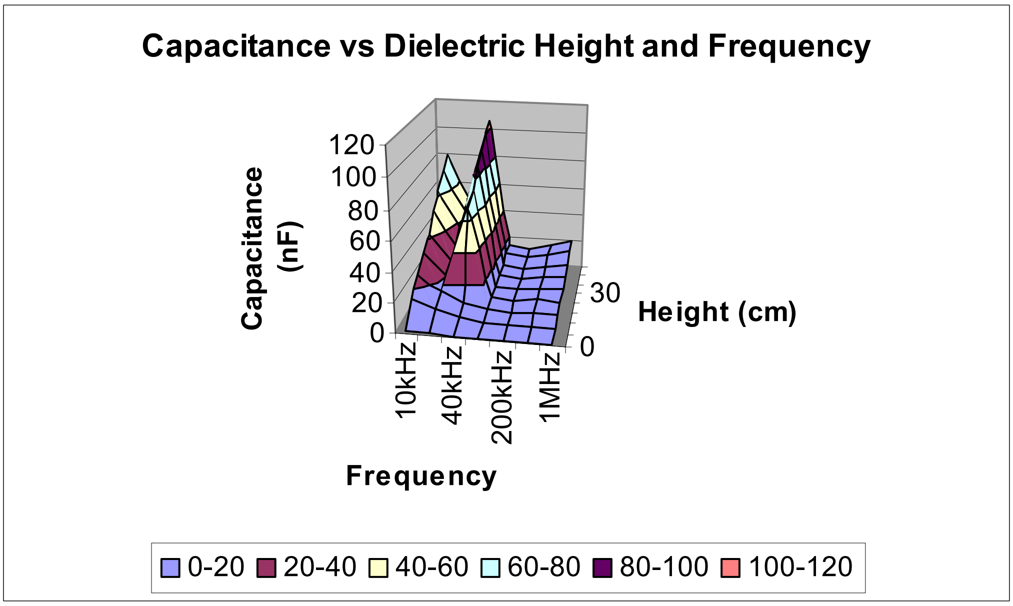

Figure 41

Plotting the resistance component of the impedance versus the height of the dielectric and the frequency yields the following graph:

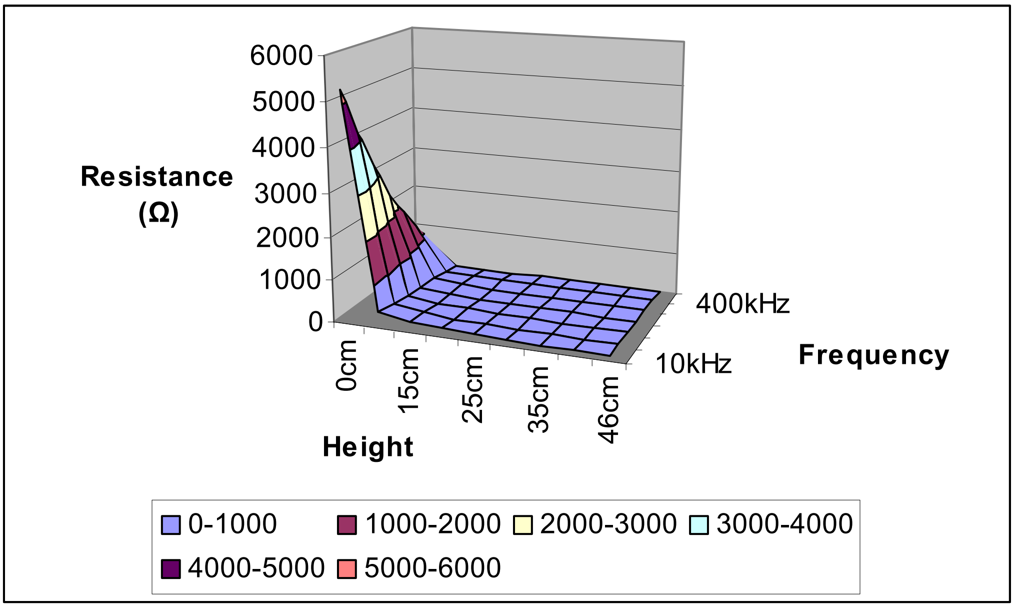

Figure 42

Examining the initial data and the graph above, one can see that the measurements taken when the dielectric height was 0cm are about ten times greater than all of the other measurements. As a result, the above graph does not depict the 10cm-46cm values accurately. If the 0cm measurements are omitted, the result is the following graph:

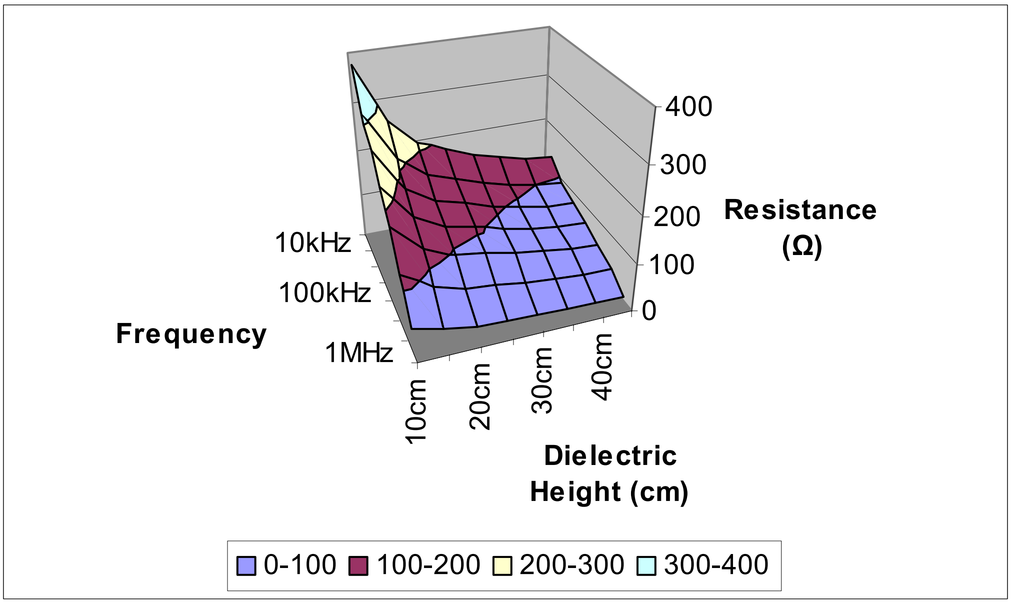

Figure 43

This new graph depicts the resistance of the capacitor more accurately.

Plotting the impedance angle versus the height of the dielectric and the frequency yields the following graph:

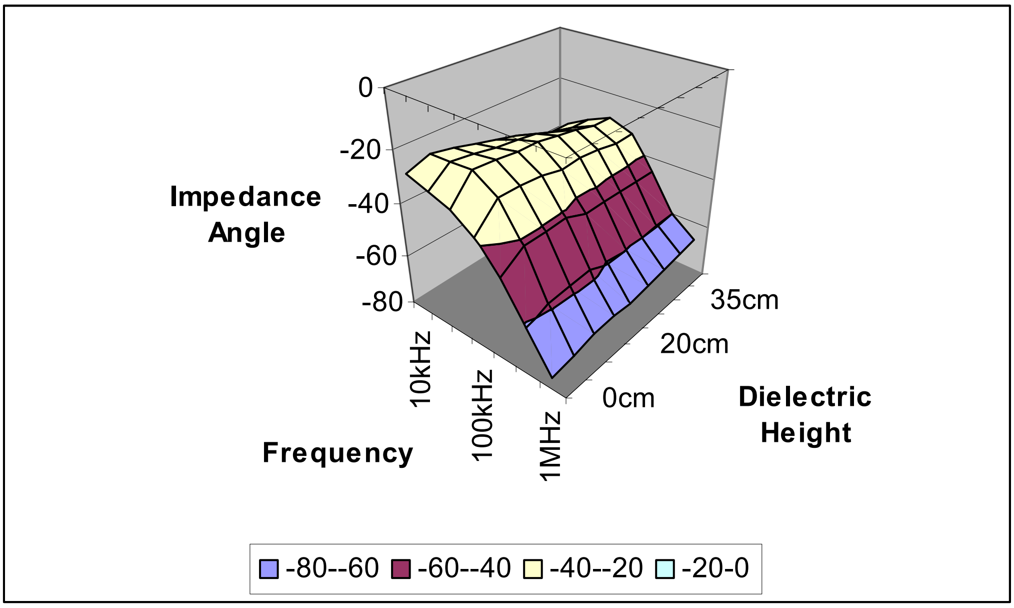

Figure 44

By analyzing the graphs plotted above, some interesting conclusions can be made about the capacitor that has been constructed. One such conclusion is that the capacitor behaves a lot like the theoretical behavior discussed in the beginning of this paper when the test frequency applied is over 200kHz. This applies to the total capacitance as the impedance angle starts to approach the theoretical value of –90° when the test frequency is about 1MHz.

The impedance values measured consist of a resistance and an angle. These two values together constitute an impedance vector that is stated in polar coordinates as shown in the figure below.

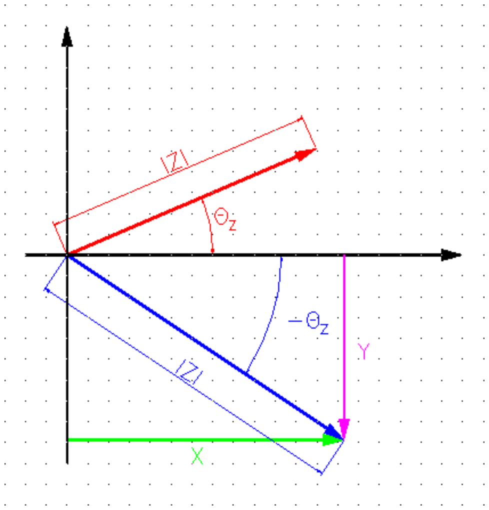

Figure 45

To convert the polar coordinates to Cartesian coordinates, the following equations are used:

$$X = Z \quad \cos(\theta_Z)$$
$$Y = Z \quad \sin(\theta_Z)$$

The following table shows the corresponding X & Y values that were calculated from the initial measurements table:

	10kHz	20kHz	40kHz	100kHz	200kHz	400kHz	1MHz
0cm (X)	4726.5	3637.3	2792.4	1888.6	1209.1	581.8	157.3
(Y)	-2397.9	-2100.0	-1758.5	-1480.9	-1333.4	-1049.5	-579.0
10cm (X)	354.4	288.8	247.4	198.3	136.0	64.1	14.6
(Y)	-155.6	-123.2	-103.0	-110.4	-122.5	-103.8	-48.9
15cm (X)	241.2	194.9	166.8	132.6	91.4	44.2	10.3
(Y)	-114.5	-88.4	-72.9	-74.4	-80.8	-69.1	-31.4
20cm (X)	187.2	150.1	128.1	102.4	71.0	34.0	7.9
(Y)	-97.4	-73.2	-58.9	-58.6	-63.1	-53.0	-22.7
25cm (X)	162.1	132.1	114.3	91.3	59.4	25.9	5.7
(Y)	-93.2	-66.7	-53.1	-55.7	-59.4	-46.2	-18.1
30cm (X)	136.8	110.6	95.5	76.2	50.8	22.6	4.9
(Y)	-86.8	-60.3	-46.0	-46.0	-49.6	-38.9	-14.2
35cm (X)	120.8	96.0	82.4	65.1	43.2	18.9	4.1
(Y)	-85.5	-57.7	-43.1	-41.1	-43.1	-33.0	-11.3
40cm (X)	106.7	84.1	71.8	56.1	37.1	16.3	3.7
(Y)	-81.0	-54.2	-39.6	-36.6	-37.8	-28.7	-9.3
46cm (X)	99.3	78.4	66.1	52.7	34.5	15.0	3.5
(Y)	-77.6	-51.9	-37.4	-34.5	-34.8	-26.0	-8.3

Table 8

Using the above X & Y values to plot the impedance based on the frequency yields the following graph depicted by figure 46. The 0cm values have been excluded, as they are not consistent with the other values, and this is expected because in this case the capacitor is filled with air only.

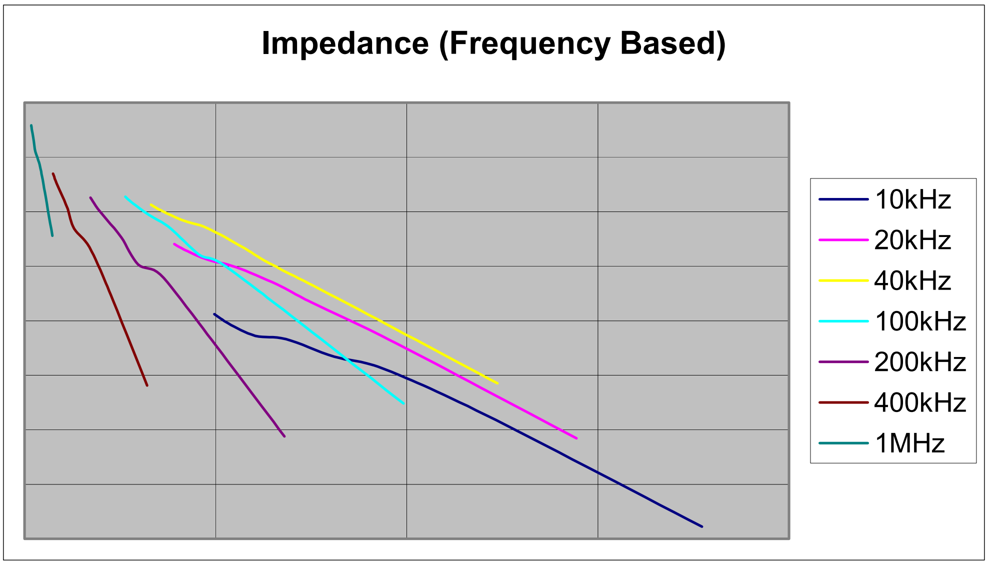

Figure 46

The same X & Y values can be used to produce an impedance graph based on the height of the dielectric. As the 0cm values ten times larger in magnitude compared to all of the other values, a separate graph was made for this dielectric height. These two graphs are shown below, depicted by figures 47 and 48:

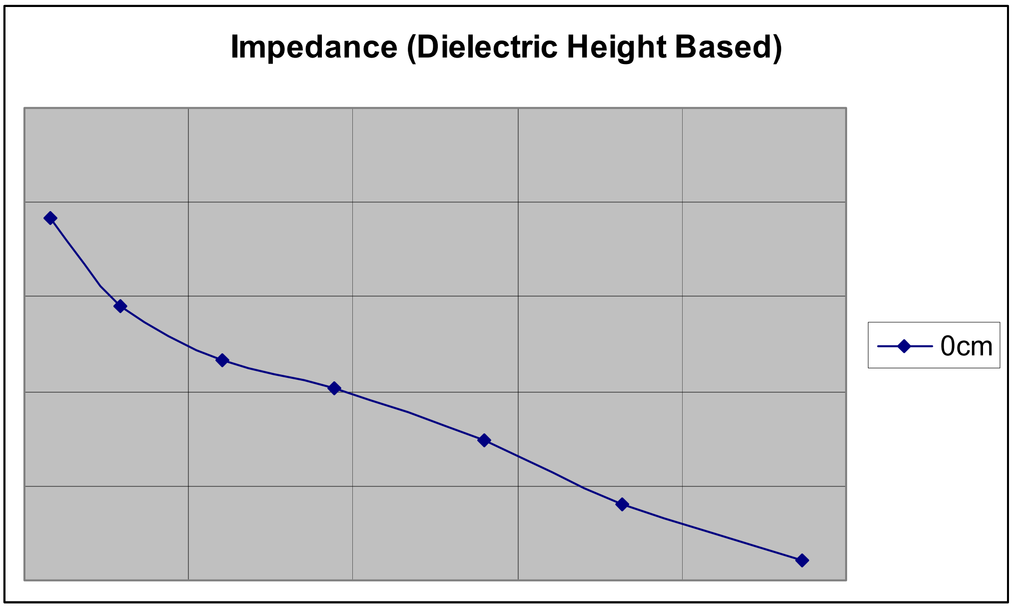

Figure 47

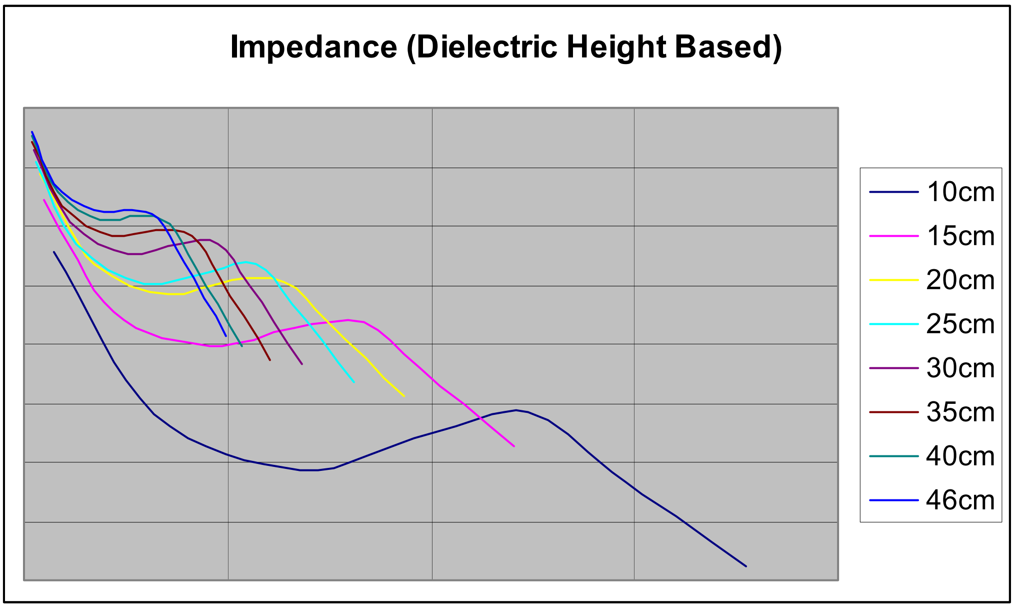

Figure 48

From the above graphs and in addition to the frequency based impedance graph, one can see that the resulting impedance curve is dependent on the test frequency. The magnitude of the resistance depends on the height of the dielectric.

As the impedance curve based on the dielectric height for 0cm differs from the other impedance curves based on the dielectric height, one can assume that this is due to the coat of varnish that hasn’t coated the copper pipes entirely. The surface that is not covered with the coat of varnish contributes to electrolysis and this affects the overall capacitance. This results in the capacitor’s “non-ideal capacitor” behavior and the resulting graphs.

10. CONCLUSIONS AND FURTHER DEVELOPMENTS

10.1 CONCLUSIONS

Every effort was made in this project to present numerous alternatives for every task being performed. This allowed the end user to determine which alternative was best suited to the task at hand and it also ensured that a successful end result was achieved.

There are many conclusions that can be drawn from all of the data that was collected and analyzed within the scope of this project. A basic capacitance theory was examined and a capacitor was constructed. As a result of initial measurements, this capacitor was improved so its modified behavior could be investigated. This led to a capacitor that provided very good results and also allowed it to be used as a very good sensor in determining the height of a liquid. This resulting sensor showed all of the desired characteristics of a sensor for linearity and discreteness.

Taking all of the information gathered in this thesis project one step further, one could further develop the concepts studied here and could improve upon some of the shortcomings that were discovered. The entire system that was investigated in the project, which consisted of the power supply circuit, the capacitor charging/discharging circuit, the microcontroller application and the capacitor that was constructed, can easily be used as a stand-alone product for various applications. These example applications and suggestions for further improvements will be discussed in the next section.

10.2 IMPROVEMENTS

This project, like all others, always has room for further improvements and developments. This is also evident in systems that are commercially available where upgrades are released periodically that correct faults from previous versions or new features and functionalities are added. There are two areas of development that can be applied to the capacitors that were built in this project. The first area is a better type of construction and the second area is the custom construction of the capacitor for specialized applications.

10.2.1 CAPACITOR CONSTRUCTION IMPROVEMENTS

The basic improvement that is necessary for the construction of the capacitors is the proper coating of varnish to prevent electrolysis. This can be achieved by dipping the copper pipes into a varnish bath so as to ensure that the coating is uniform throughout the whole length of the copper pipes.

Another way to eliminate the electrolysis phenomenon is to coat the copper pipes with a liquid epoxy-type compound, provided that this coating is very thin. The type of coating would also allow the capacitor to measure the level of a solvent that would normally dissolve the coat of varnish. These types of solvents may include several types of fuels or certain corrosive chemicals.

10.2.2 SAMPLE APPLICATIONS

The capacitance phenomena analyzed throughout this project could be used in many real-life applications. There are two ways of using the capacitor that was constructed. The first method involves using the capacitor to measure the height of a liquid whereas the second method is to use the capacitor to detect a change in the liquid.

For example, a common problem in automobiles when they age is that the flanges between the pieces of metal of the engine block break down either due to age and/or exposure to high temperatures. These flanges keep the water based anti-freeze mixture that is used to cool the engine separated from the engine oil that lubricates and circulates in the pistons’ oil rings. Should the flanges break down, the two different liquids will mix and contaminate each other, resulting in the potential damage of the engine. If left long enough, the anti-freeze and oil mixture create a soapy liquid that is damaging to the engine, radiator and to the oil pump. The capacitor used in this project could be used to detect this type of leak and subsequent mixture from an early stage. If the engine oil is allowed to flow through the copper pipe capacitor, the capacitance will be a certain constant value based on the dielectric constant of the oil. Should a leak occur, the oil would be mixed with the water based anti-freeze solution and the dielectric constant would be altered. As the relative permittivity of oil is $\boldsymbol{\varepsilon_r} = 2.3$, and the relative permittivity of distilled water $\boldsymbol{\varepsilon_r} = 80$, the resulting capacitance would increase significantly and this increase could be detected by the microcontroller which in turn could activate a warning light. The capacitor could also be placed on the anti-freeze system, something that is easier to implement in an engine as this system has many rubber tubes that can be tapped. Similarly, should oil enter the water based liquid, the capacitance would change due to a new dielectric constant, although the change would not be as great since the oil's relative permittivity is a lot less than water's. In this case the sensor would have to be more accurate to detect the smaller change, something that could be done by fine-tuning the A/D circuit of the microcontroller. A car's 12V battery or a truck's 24V battery could be used to apply the voltage to the capacitor and a voltage regulator could provide +5V DC to the remaining circuit.

A second example of how this capacitor could be used in a real-life application is the following. Certain gas station owners may dilute the gas or diesel fuel they sell with water. The capacitor constructed in this project could be used to perform spot checks of the gas station's deposit tanks to verify that no dilution has taken place. As the various fuels have a lower density than water, they tend to float to the top while the water remains on the bottom, undetectable to the naked eye. A one meter capacitor could be constructed with the copper pipes used in this project. This capacitor could be calibrated with various types of fuel and the total capacitance could be calculated. In turn, this one meter capacitor could be dipped into the gas station's deposit tanks and a reading could be taken. Should water exist at the bottom of the tank, the total capacitance would be the capacitance due to the height of the water in the pipes plus the capacitance due to the height of the fuel. If the water and fuel mixture has not had enough time to settle, then the capacitor will still measure an altered capacitance as the dielectric between the copper pipes will consists of both water and the fuel in question, thus giving a different result compared to fuel only. The microcontroller can be programmed via a selector switch as to the type of fuel in question and a liquid crystal display could be used to display "OK" or "Not OK". For a more economical solution, two light emitting diodes could be used, a green one for "Ok" and a red one for "Not Ok". A third solution would be the use of a buzzer where an audible beep could signify whether the fuel was diluted or not.

A third application could be the use of the capacitor to control the mixture of several liquids in the chemical or pharmaceutical industry. Each liquid component of a mixture would have a unique dielectric constant based on the permittivity of the liquid. When two or more liquid are to be mixed together, the resulting dielectric constant should also be unique. Based on this information, the microcontroller could use the input from the capacitor to control several servomotors that in turn would control the amount of liquid being mixed. The accomplishment is a system that accurately controls the mixing process of several liquids. The microcontroller could also control an electrical valve that would open and allow the mixture to flow to a holding tank only when the final mixture contained the proper ratios of the initial liquids. If the final mixture was not correct, the microcontroller could close the valve thus redirecting the output to a waste tank. The waste produced could be considered a disadvantage in this case.

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12. APPENDICES

APPENDIX A: OSCILLOSCOPE OUTPUT

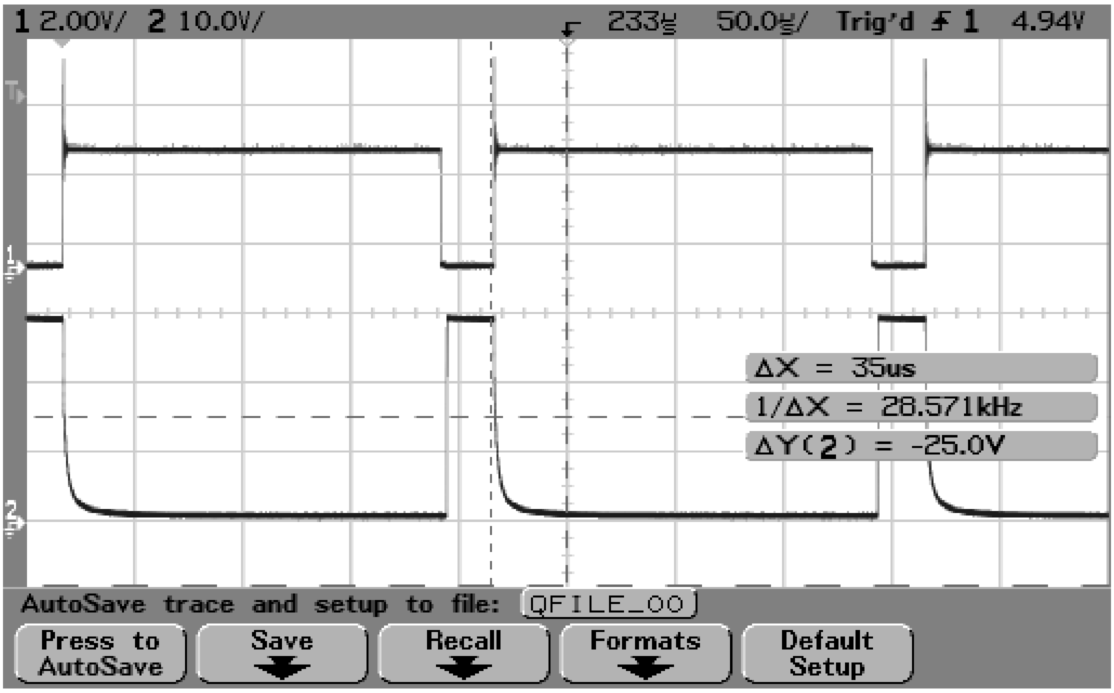
APPENDIX B: TIGER BASIC PROGRAM CODES

APPENDIX C: TIMERA DEVICE DRIVER FREQUENCY RANGE TABLES

APPENDIX D: DATASHEETS

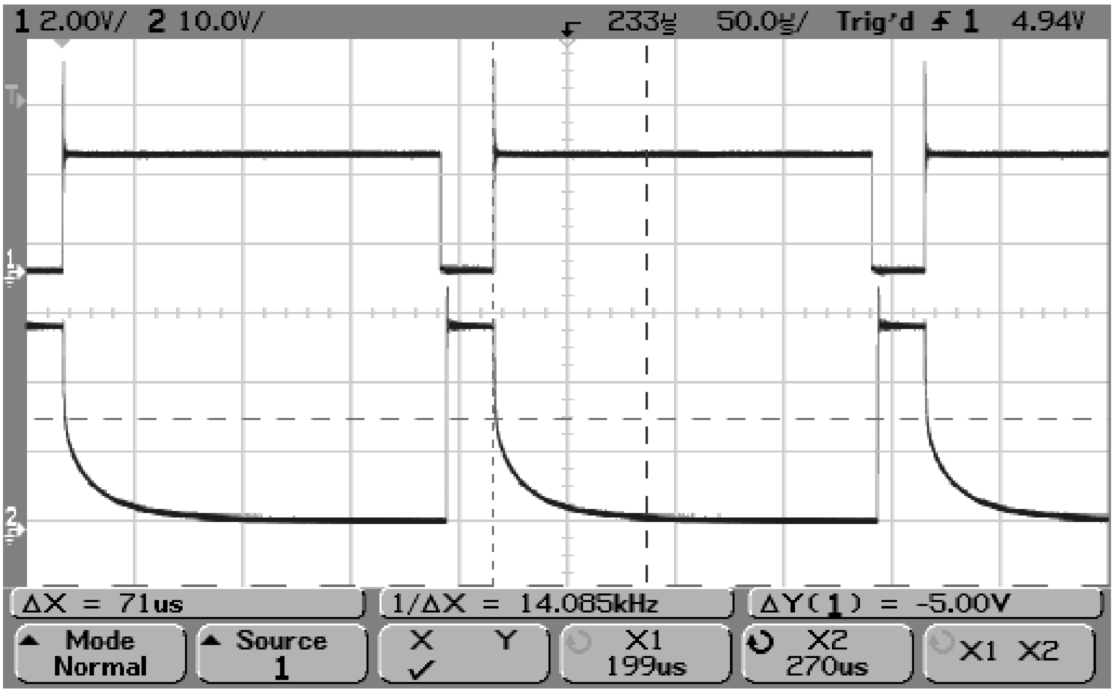
12.1 Appendix A: Oscilloscope Output

12.1.1 Initial capacitor response measurements



```
1 2.00V/  2 10.0V/        233µs   50.0µs/   Trig'd ⨍ 1   4.94V
ΔX = 35us
1/ΔX = 28.571kHz
ΔY(2) = -25.0V
AutoSave trace and setup to file: QFILE_00
```

Figure 49 (0cm Water)



```
1 2.00V/  2 10.0V/        233µs   50.0µs/   Trig'd ⨍ 1   4.94V
ΔX = 71us   1/ΔX = 14.085kHz   ΔY(1) = -5.00V
Mode Normal   Source 1   X Y ✓   X1 199us   X2 270us   X1 X2
```

Figure 50 (10cm Water)

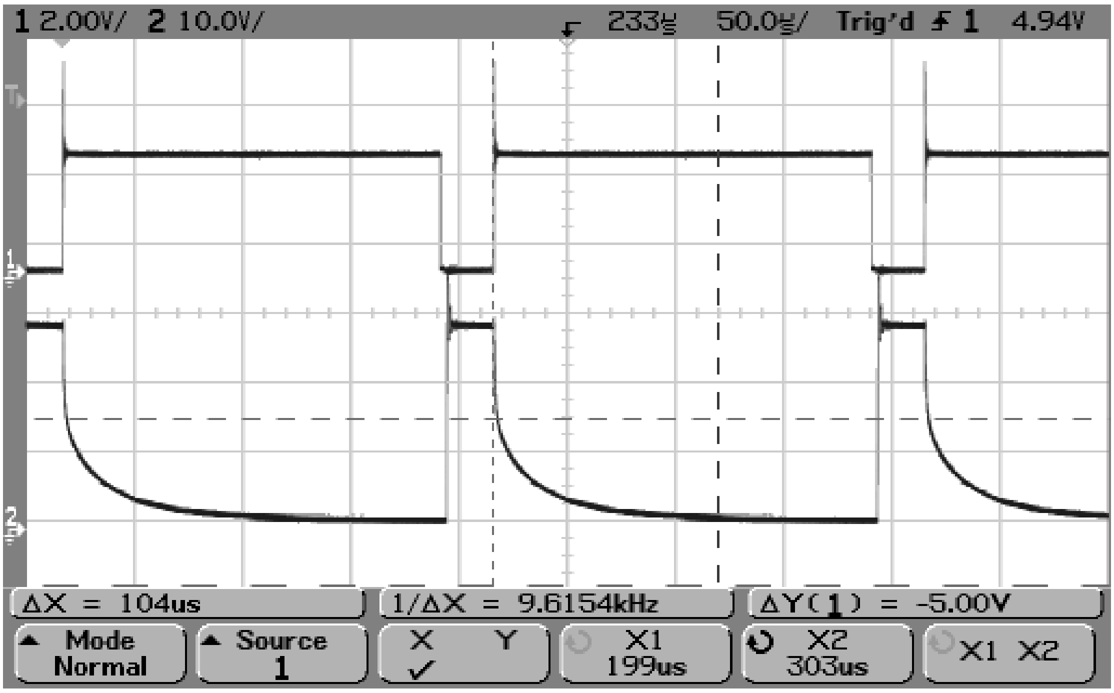


Figure 51 (20cm Water)

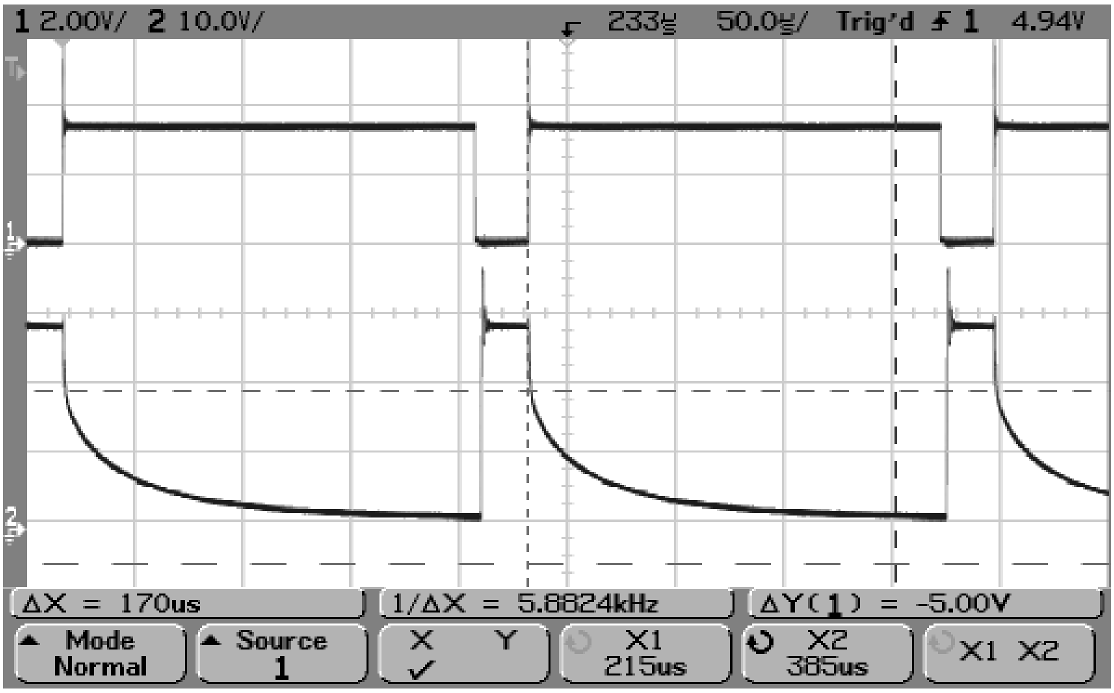
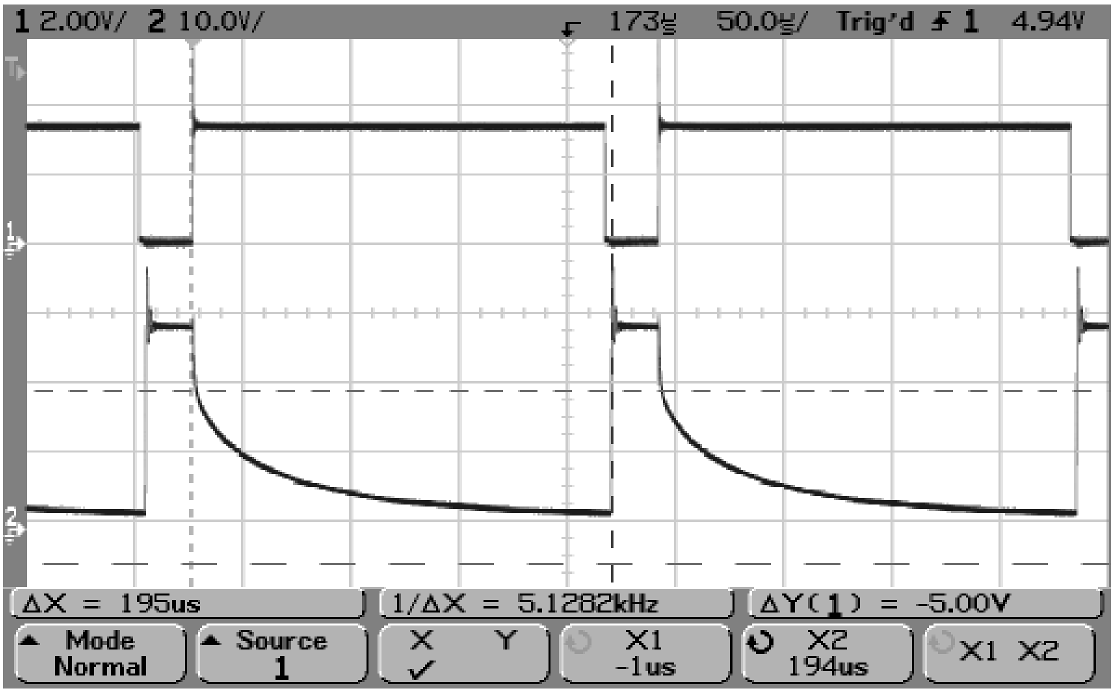


Figure 52 (30cm Water)

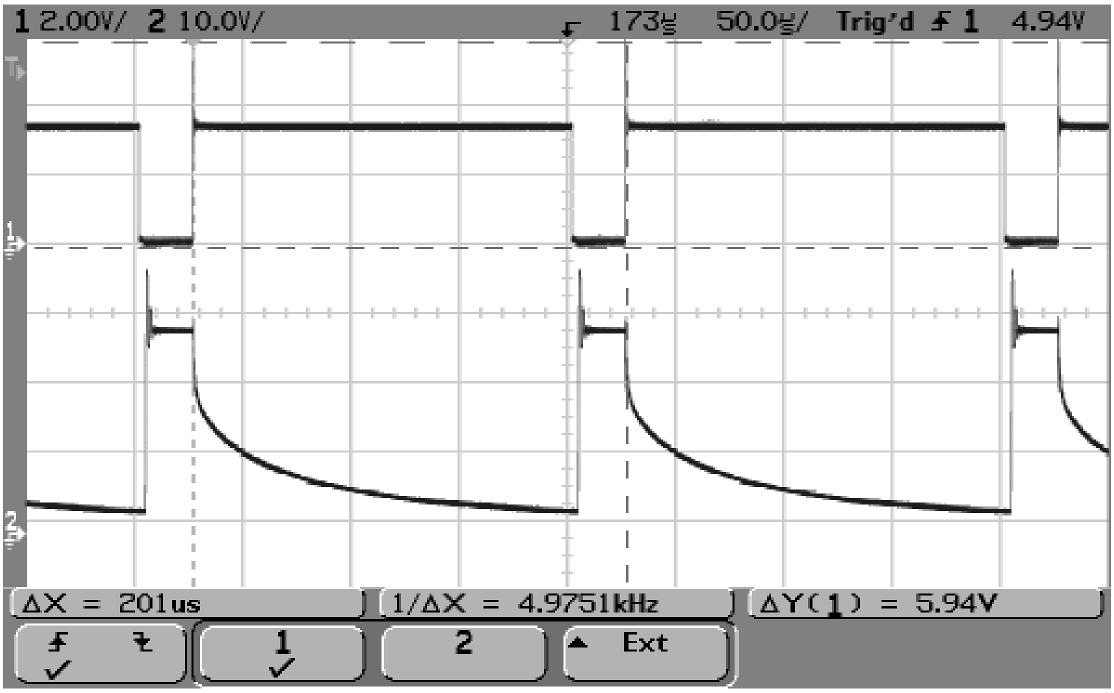


ΔX = 195us

1/ΔX = 5.1282kHz

ΔY(1) = -5.00V

Figure 53 (40cm Water)



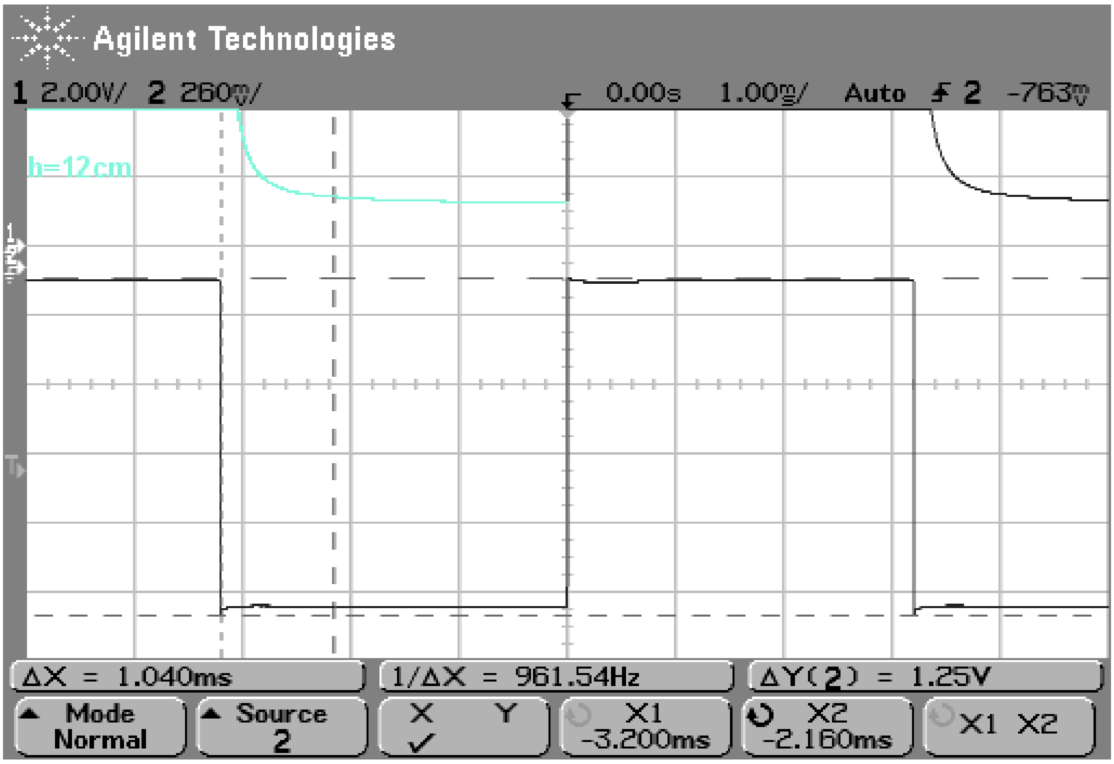
ΔX = 201us

1/ΔX = 4.9751kHz

ΔY(1) = 5.94V

Figure 54 (50cm Water)

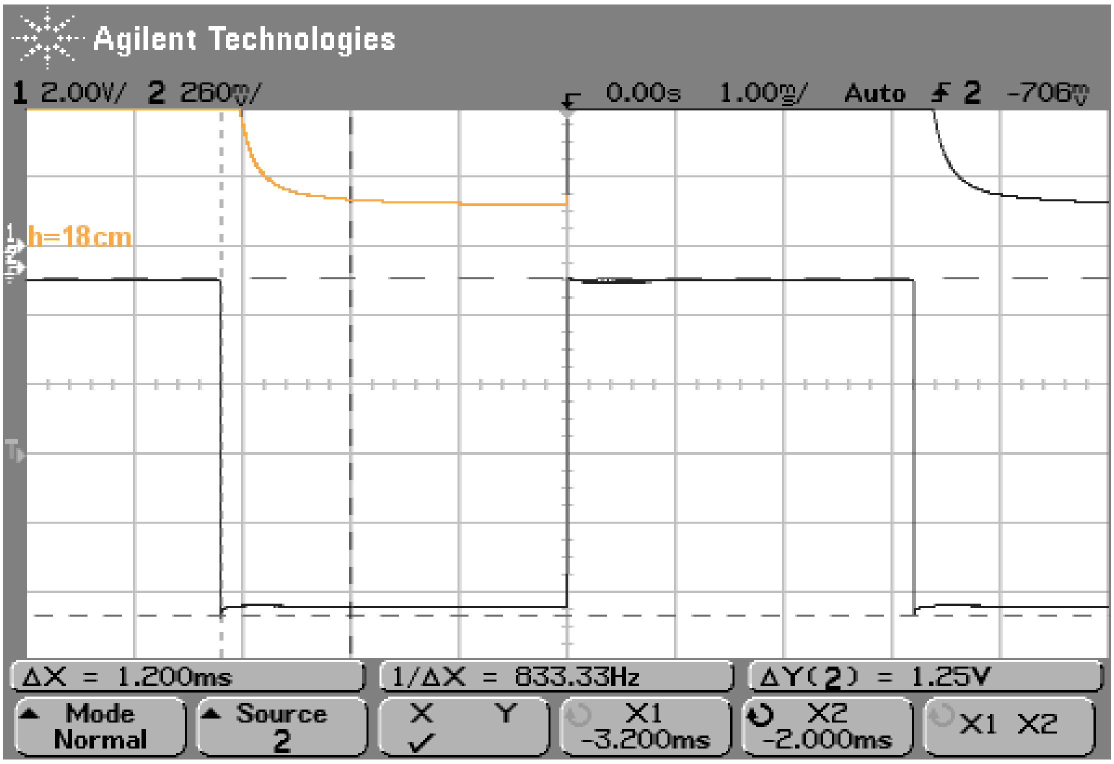
12.1.2 Tiny Tiger Measurements



1 2.00V/ 2 260mV/ 0.00s 1.00ms/ Auto 2 -763mV

ΔX = 1.040ms 1/ΔX = 961.54Hz ΔY(2) = 1.25V

Figure 55



1 2.00V/ 2 260mV/ 0.00s 1.00ms/ Auto 2 -706mV

ΔX = 1.200ms 1/ΔX = 833.33Hz ΔY(2) = 1.25V

Figure 56

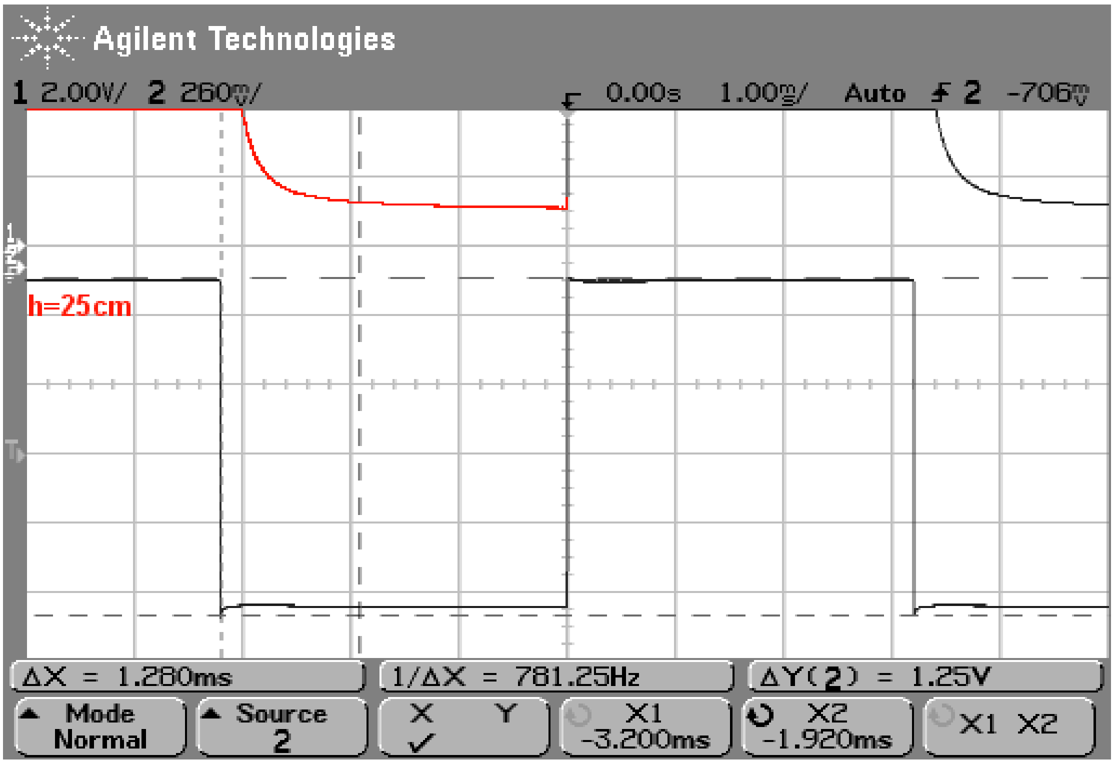


Figure 57

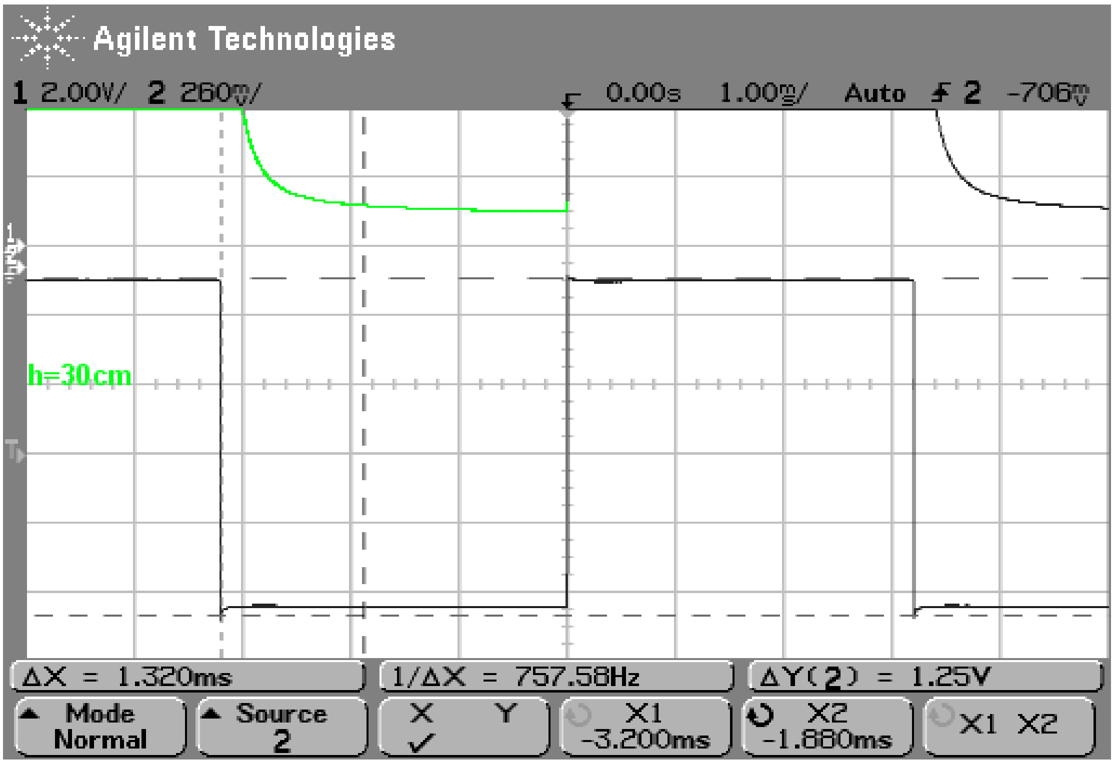


Figure 58

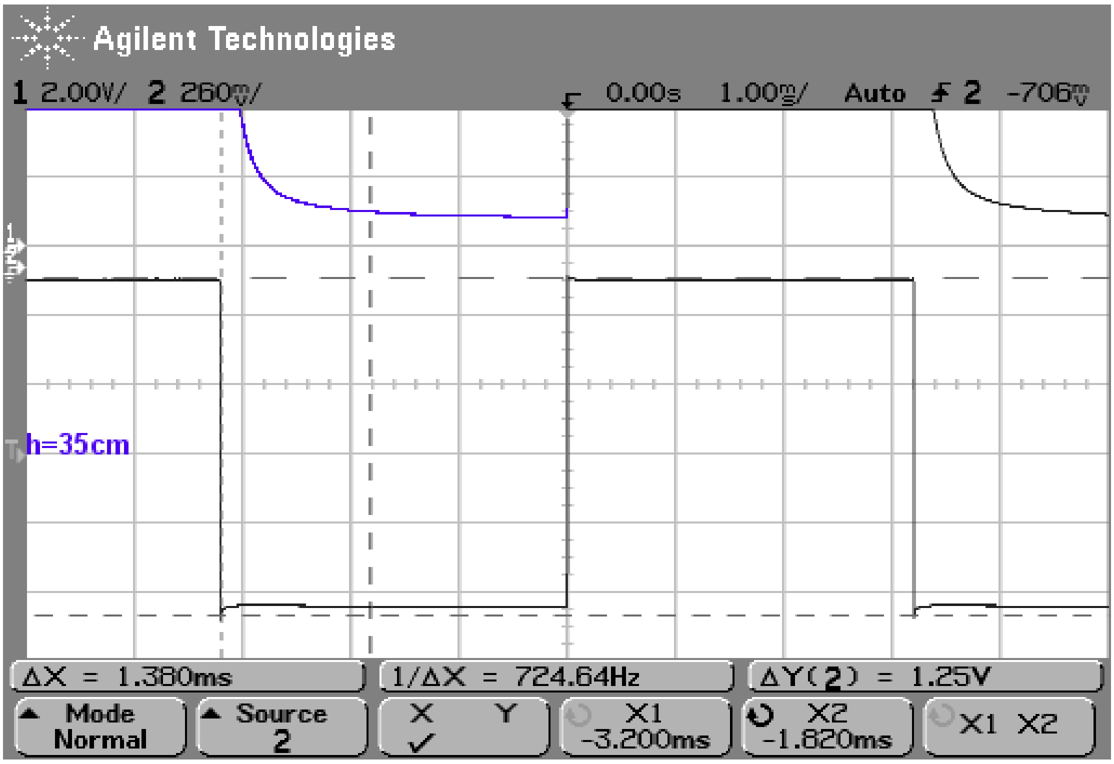


Figure 59

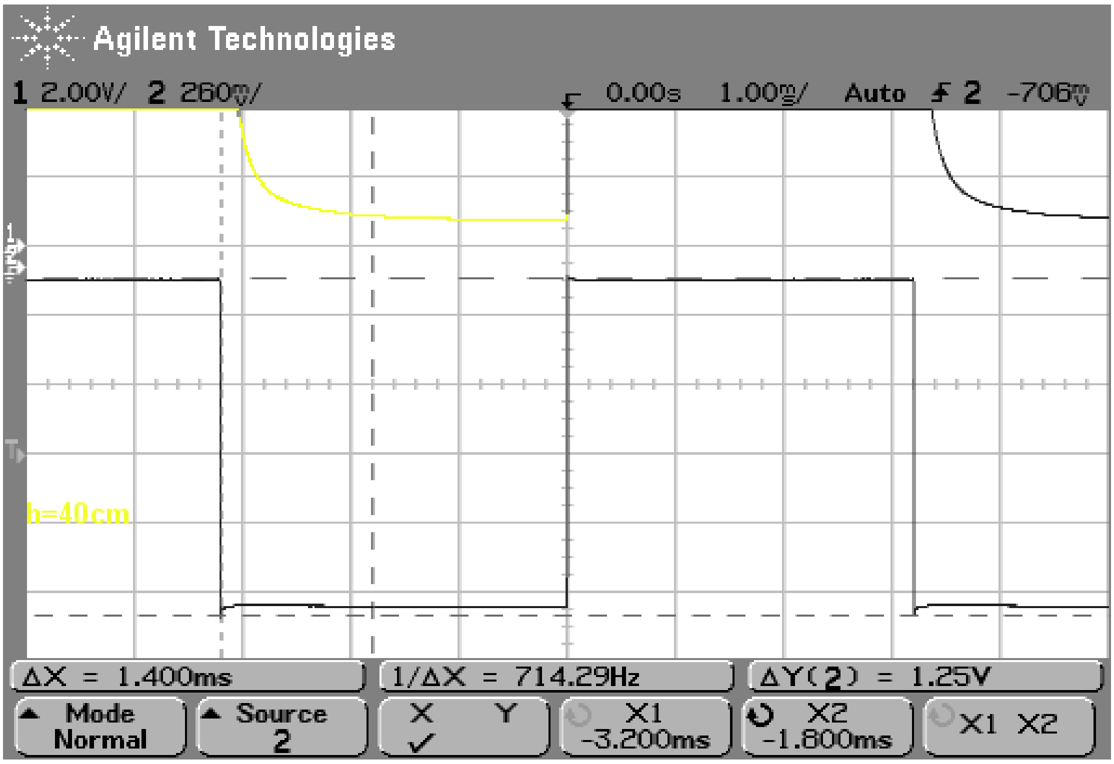


Figure 60

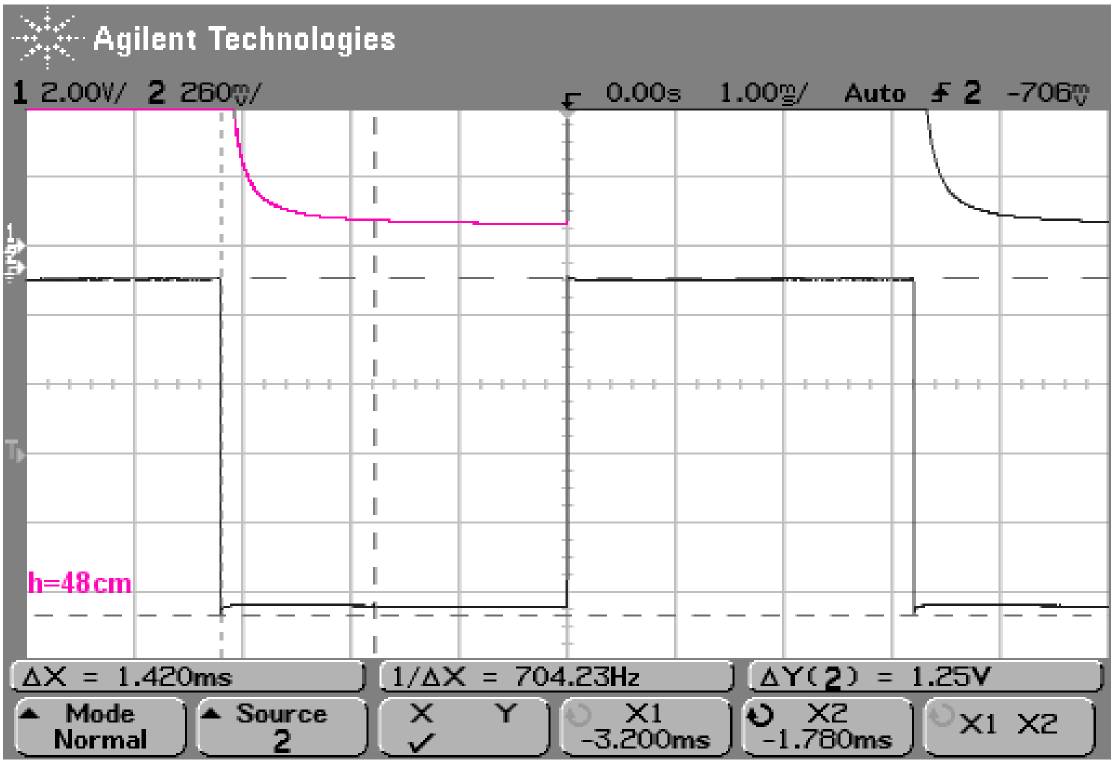

Agilent Technologies
1 2.00V/ 2 260mV/
0.00s 1.00ms/ Auto 2 -706mV
h=48cm
ΔX = 1.420ms
1/ΔX = 704.23Hz
ΔY(2) = 1.25V
Mode Normal
Source 2
X Y
X1 -3.200ms
X2 -1.780ms
X1 X2

Figure 61

12.1.3 Final 555-Timer Measurements (45cm Capacitor)

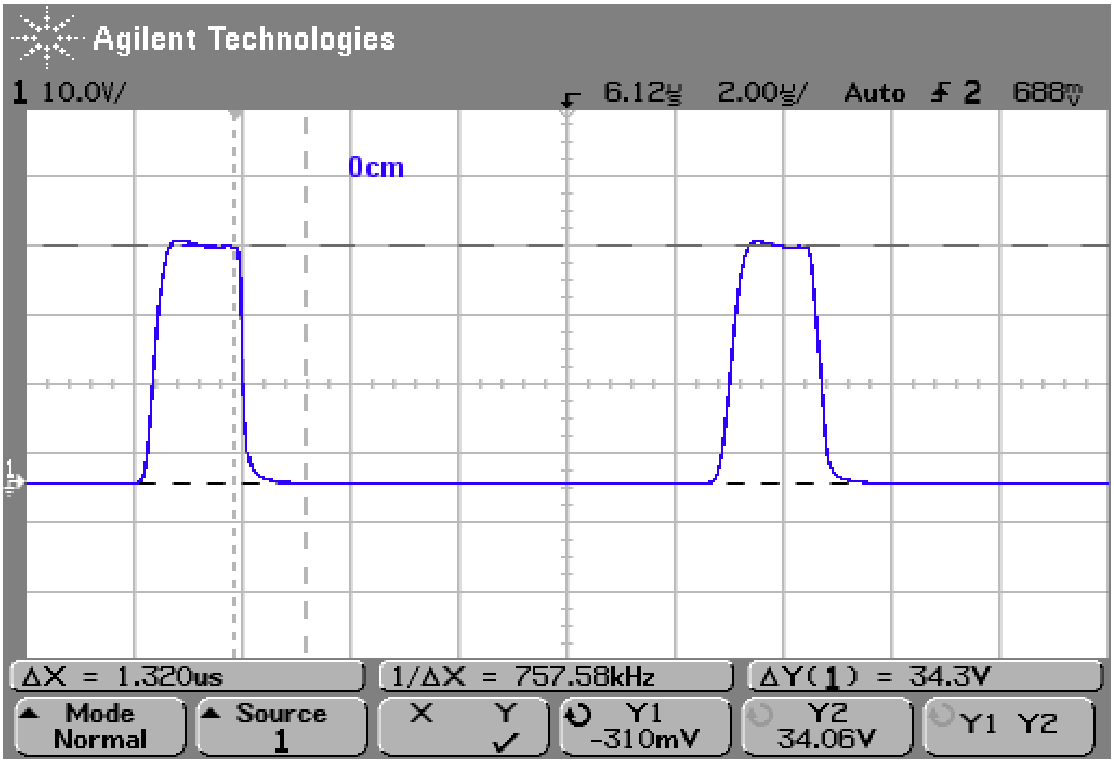


Figure 62

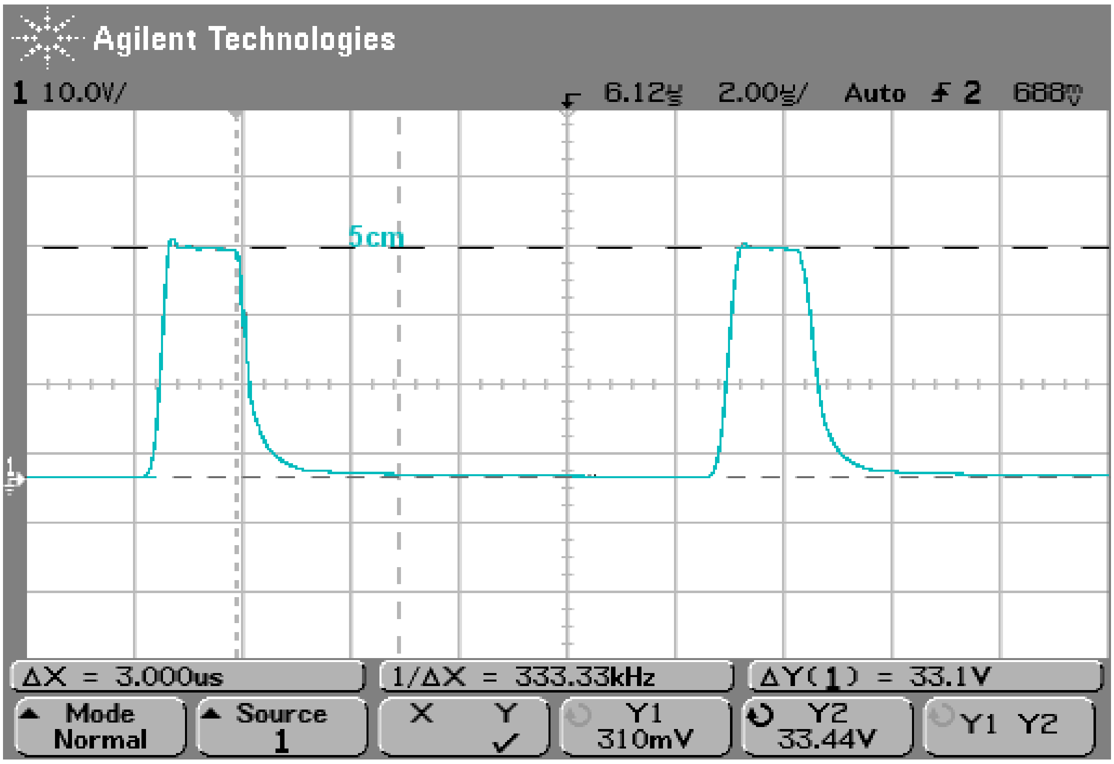


Figure 63

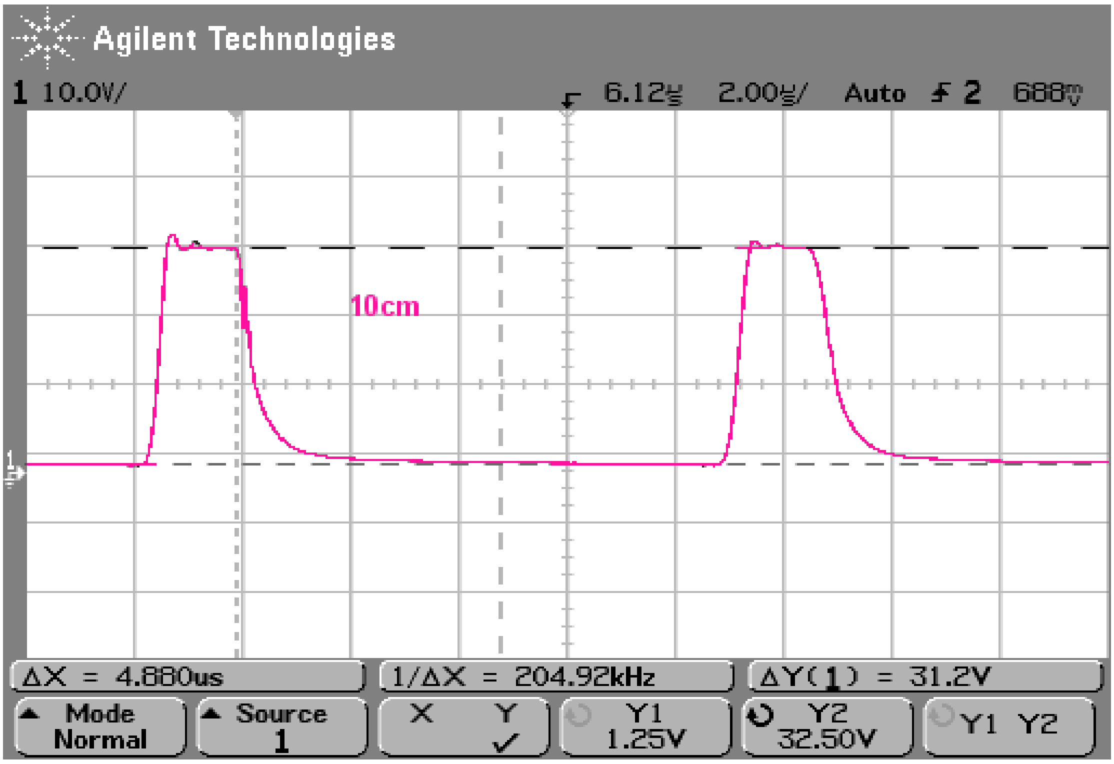


Figure 64

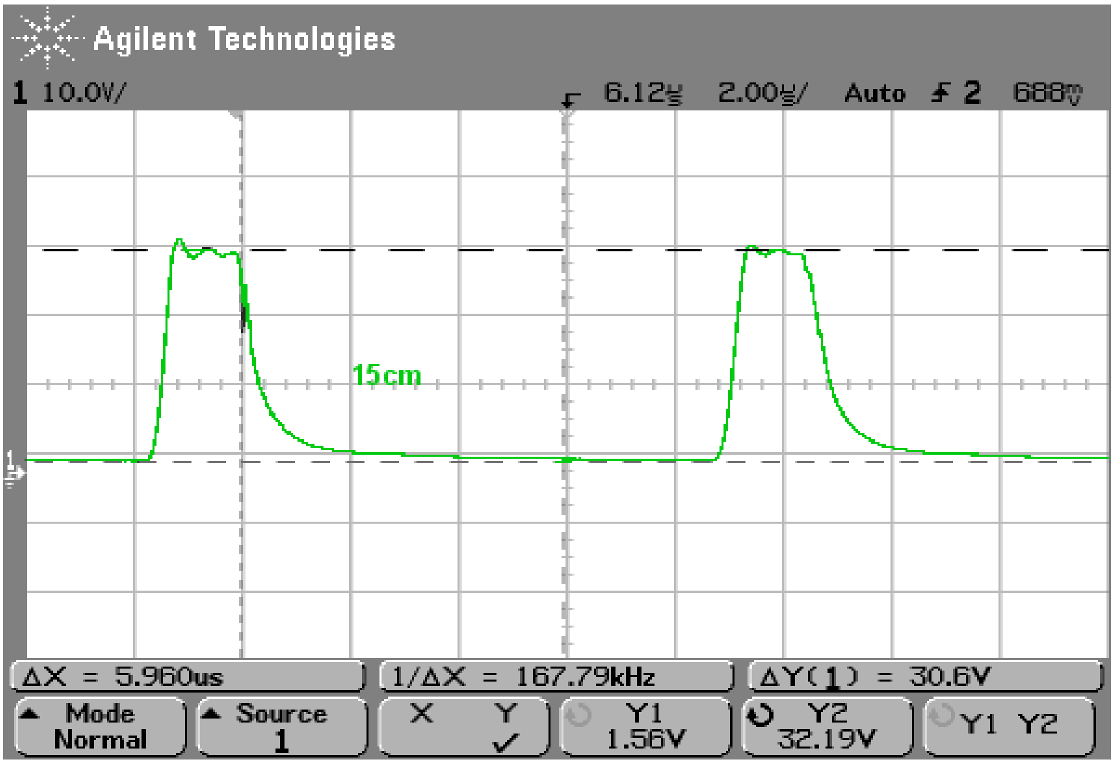


Figure 65

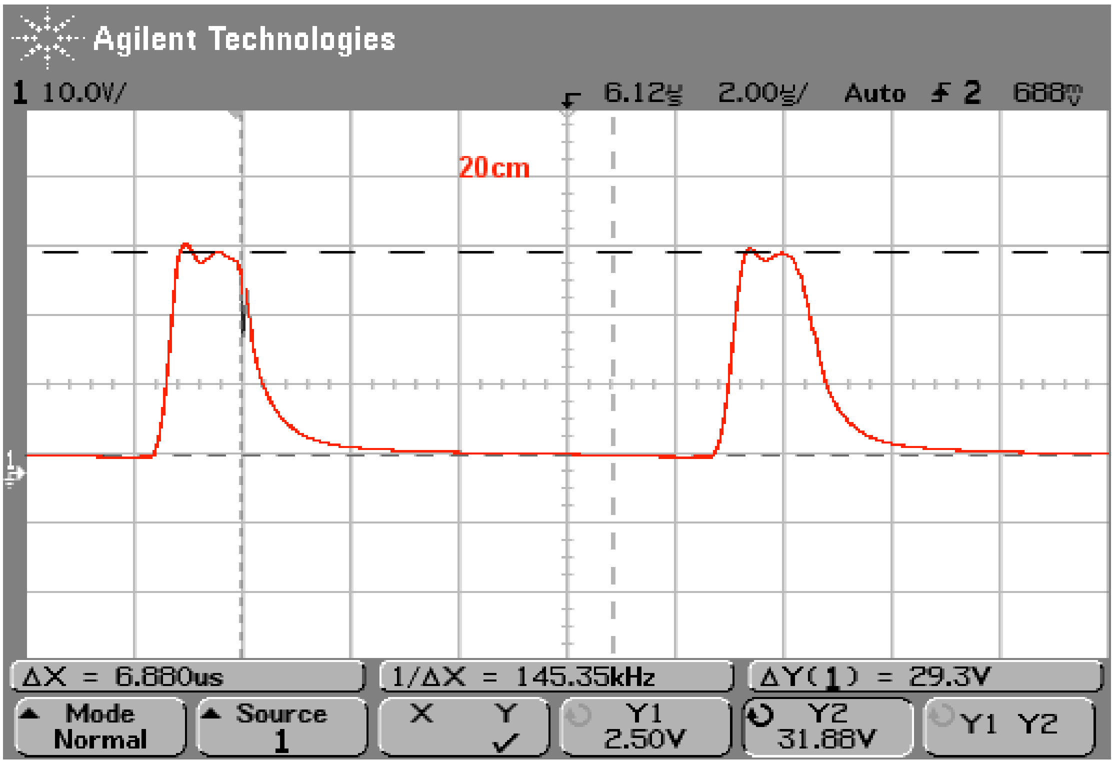


Figure 66

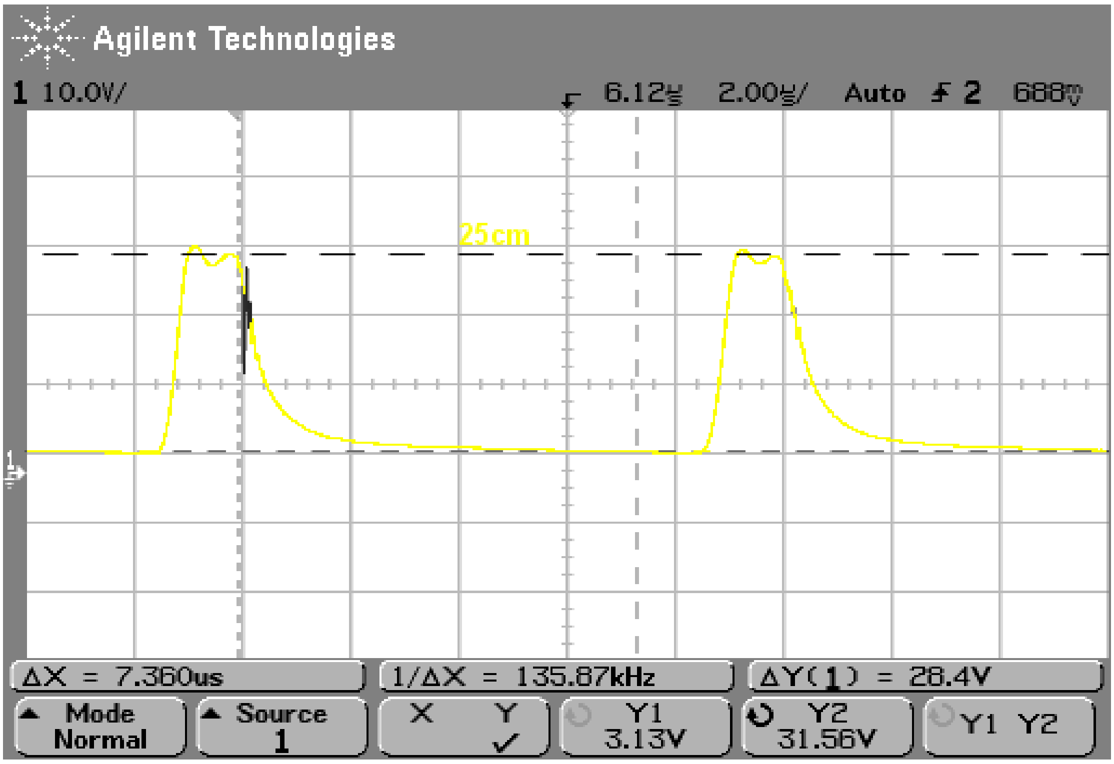
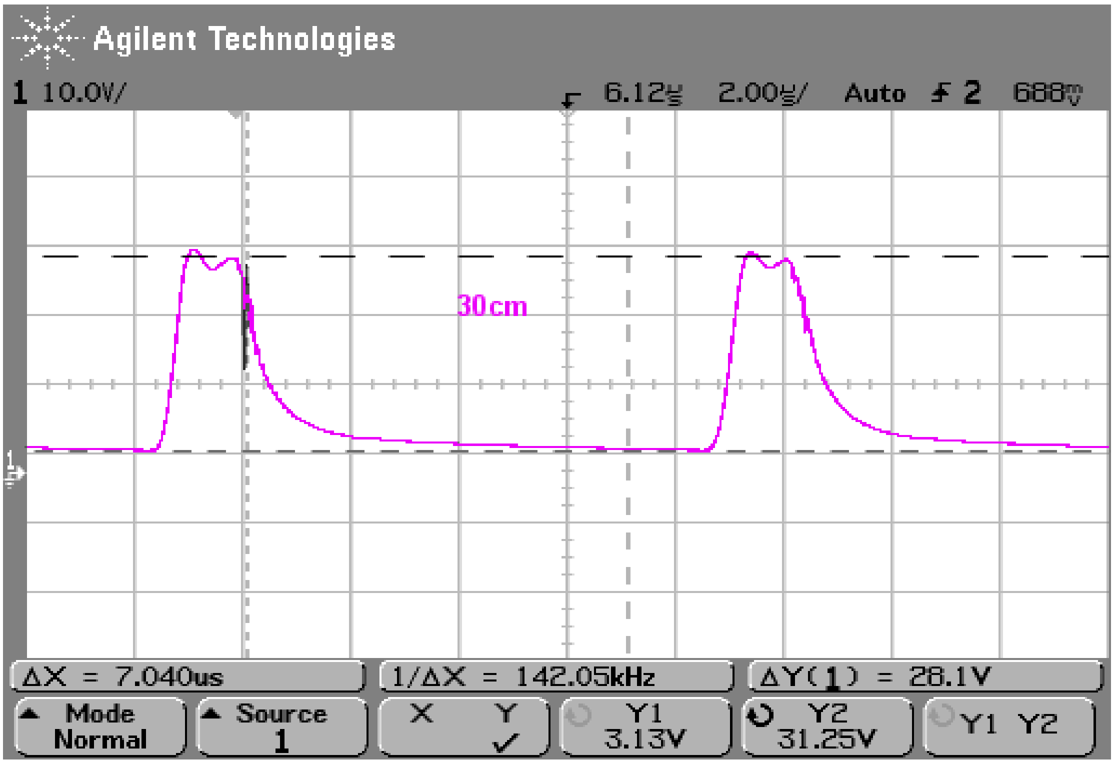


Figure 67



1 10.0V/ 6.12us 2.00us/ Auto 2 688mV

ΔX = 7.040us

1/ΔX = 142.05kHz

ΔY(1) = 28.1V

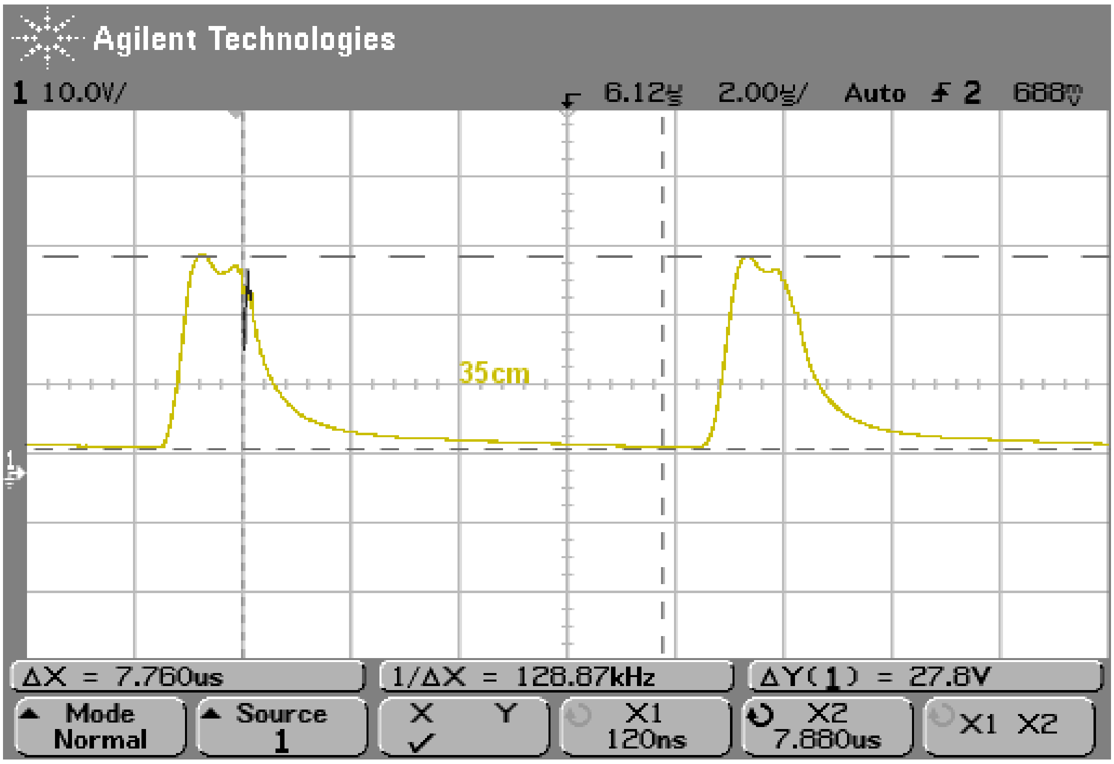
Mode Normal

Source 1

Y1 3.13V

Y2 31.25V

Figure 68



1 10.0V/ 6.12us 2.00us/ Auto 2 688mV

ΔX = 7.760us

1/ΔX = 128.87kHz

ΔY(1) = 27.8V

Mode Normal

Source 1

X1 120ns

X2 7.880us

Figure 69

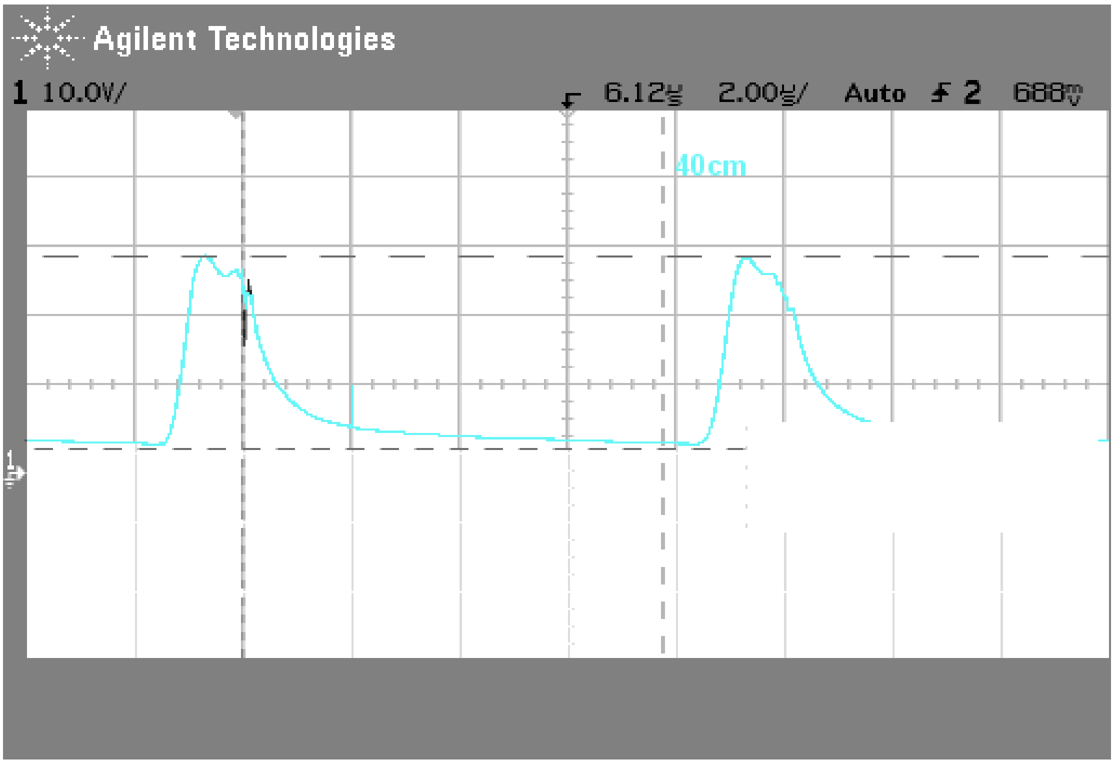


Figure 70

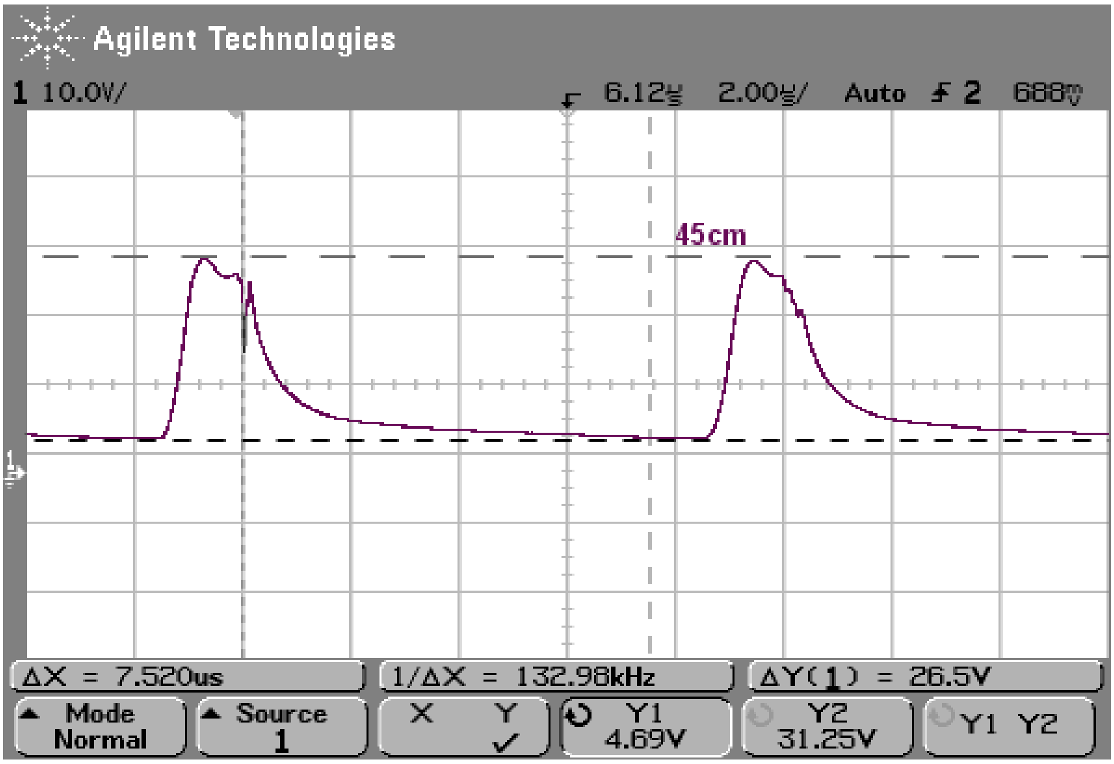
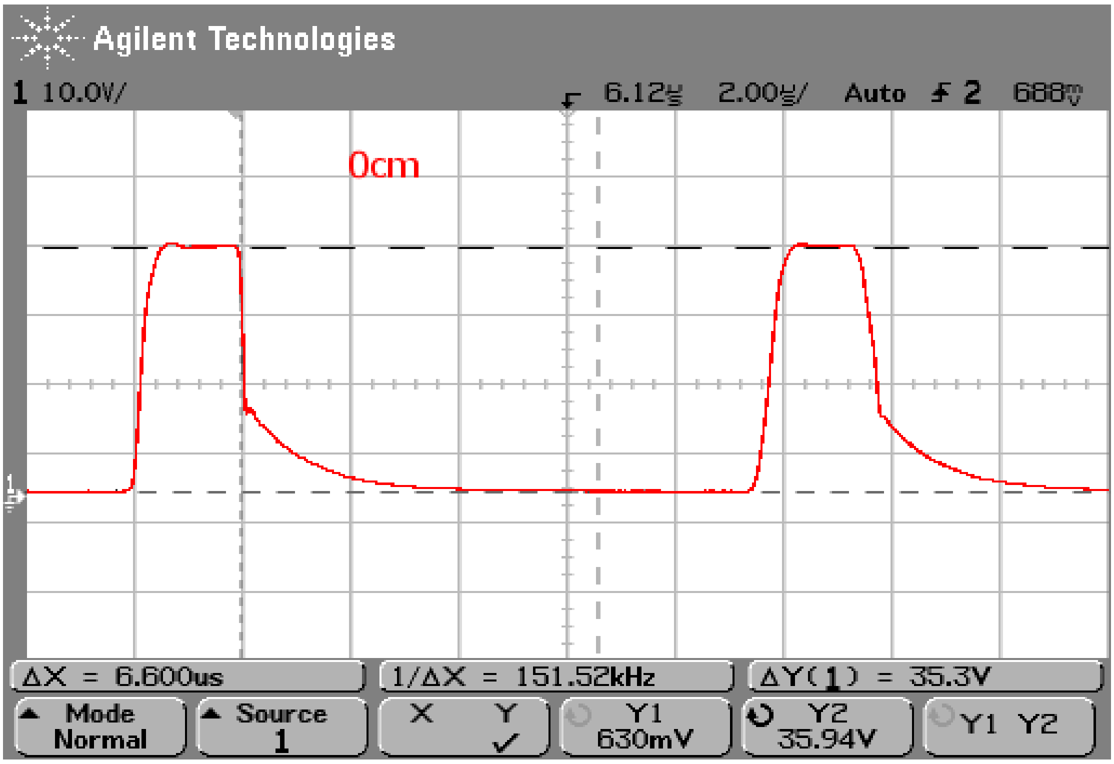


Figure 71

12.1.4 Final 555-Timer Measurements (75cm Capacitor)

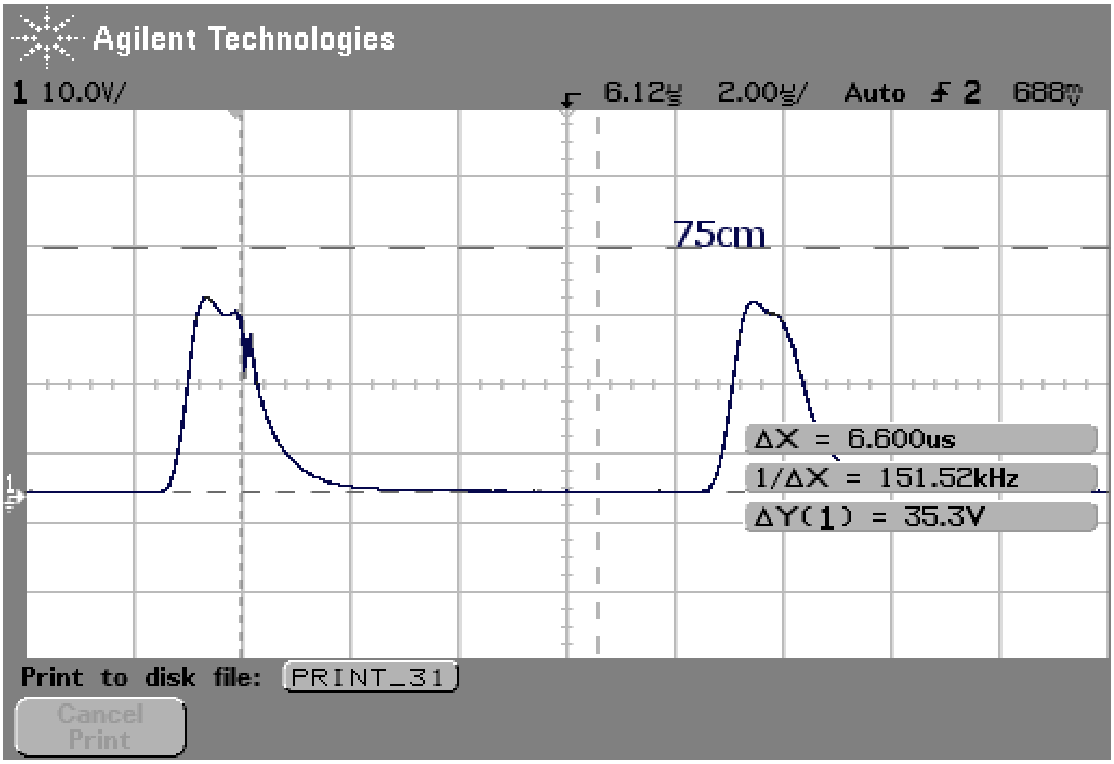


ΔX = 6.600us

1/ΔX = 151.52kHz

ΔY(1) = 35.3V

Figure 72 (0cm Water)



ΔX = 6.600us

1/ΔX = 151.52kHz

ΔY(1) = 35.3V

Print to disk file: PRINT_31

Figure 73 (75cm Water)

12.2 APPENDIX B: TIGER BASIC PROGRAM CODES

12.2.1 MAIN PROJECT PROGRAM

```
'----------------------------------------------------------------------
' Name:   Capacitor_Discharge.TIG (Main Program)
' Author: Alex Toulouzas
' Description: This program will generate a square wave pulse on pin
'              6 of port 8 and will read the instantaneous A/D input
'              from A/D input 0. The program will stop executing
'              after the specified number of pulses have been output.
'----------------------------------------------------------------------
USER_VAR_STRICT                         ' compiler uses strict
                                          variable checks
#INCLUDE DEFINE_A.INC                   ' general defines
#INCLUDE UFUNC3.INC                     ' User Function Codes

TASK MAIN
   LONG COUNT, CYCLE, DUTY, ATOD, N     ' variable declarations

'  install the LCD-driver (TINY-Tiger)
   INSTALL DEVICE #1, "LCD1.TDD", 0, 0, 0, 0, 0, 0, 80h, 8

'  install the ANALOG-1 driver
   INSTALL DEVICE #4, "ANALOG1.TDD"

'  install the PLSOUT1 driver for pulse output
   INSTALL_DEVICE #9, "PLSOUT1.TDD", 3  ' Time base range = 3

'  clear the LCD screen
   PRINT #1, "<1Bh>c<0><F0h>";
   PRINT #1, "<1>";

'  display the headings for the number of pulses remaining
'  and the A/D voltage
   PRINT #1, "<1Bh>A"; CHR$(0); CHR$(0); "<F0h>Remaining:";
   PRINT #1, "<1Bh>A"; CHR$(0); CHR$(2); "<F0h>Voltage:";

   COUNT = 65535                        ' 65535 pulses of length
   CYCLE = 1000                         ' 1000 x 6,4usec = 6,4msec
   DUTY = 500                           ' duty 50% = 3.2msec
   PUT #9, COUNT, DUTY, CYCLE           ' pulse output is on pin 86

   FOR N=999999999 TO 0 STEP -1         ' countdown end when N=0
      GET #9,#0,#UFCI_OPL_STAT, 4, N    ' read remaining pulses
      PRINT #1, "<1Bh>A"; CHR$(11); CHR$(0); "<F0h> "; N
      GET #4, #0, 2, ATOD               ' read A/D input
      USING "UD<5><4>*  0.0.0.2.3"
      PRINT_USING #1, "<1Bh>A"; CHR$(9); CHR$(2); 5*ATOD; "   "
   NEXT
END
```

12.2.2 Sample Program for the analog2 Device Driver

```
'---------------------------------------------------------------------
' Name:   Analog2_Sample.TIG
' Author: Alex Toulouzas
' Description: This program will charge the capacitor for 5 seconds
'              and then it will measure the discharging by using a
'              FIFO buffer. This action is done once. The reset button
'              on the Tiger module must be pressed to repeat the
'              charging & discharging sequence.
'---------------------------------------------------------------------
USER_VAR_STRICT
#INCLUDE DEFINE_A.INC                   ' general defines
#INCLUDE UFUNC3.INC                     ' User Function Codes

TASK MAIN
   FIFO SAMPLE (2048) OF WORD           ' Sample-buffer
   WORD ATOD                            ' var. for analog value
   WORD K

'  install LCD-driver (TINY-Tiger)
   INSTALL DEVICE #1, "LCD1.TDD", 0, 0, 0, 0, 0, 0, 80h, 8
'  install TIMER-A driver (time-base timer: 12500 Hz)
   INSTALL_DEVICE #2, "TIMERA.TDD", 2, 50
'  install ANALOG-2 driver
   INSTALL_DEVICE #4, "ANALOG2.TDD"

   DIR_PORT 8,0                         ' configure port 8 as output
   PUT #4,#0,#UFCO_AD2_RESO, 10         ' 10-bit resolution
   PUT #4,#0,#UFCO_AD2_SCAN, 1          ' no. of channels = 1
   PUT #4,#0,#UFCO_AD2_STOVL, 0         ' stop on overflow
   PUT #4,#0,#UFCO_AD2_PSCAL, 5         ' prescaler:12500/5=2500 S/sec
   CLEAR_FIFO SAMPLE                    ' clear the FIFO buffer

   LL_IPORT_OUT 8, 00000000b            ' set all pins on port 8 LOW

'  clear the LCD screen and display the headings
   PRINT #1, "<1Bh>c<0><F0h>";
   PRINT #1, "<1>";
   PRINT #1, "<1Bh>A"; CHR$(0); CHR$(0); "<F0h>Action:";
   PRINT #1, "<1Bh>A"; CHR$(0); CHR$(2); "<F0h>Voltage:";

   LL_IPORT_OUT 8, 00001100b            ' set pins 2&3 on port 8 HIGH
   PRINT #1, "<1Bh>A"; CHR$(8); CHR$(0); "<F0h>Charging(5s)";
   WAIT_DURATION 5000                   ' wait 5 sec
   PRINT #1, "<1Bh>A"; CHR$(8); CHR$(0); "<F0h>Discharging ";
   LL_IPORT_OUT 8, 00000000b            ' set all pins on port 8 LOW
   PUT #4, SAMPLE                       ' start measurement

   K = 0
   WHILE K < 60                         ' end when FIFO is full
      K = LEN_FIFO(SAMPLE)
      PRINT #1, "<1Bh>A"; CHR$(0); CHR$(3); "<F0h>K="; K; "    ";
   ENDWHILE

'  display the values sequentially from the FIFO buffer
   FOR K = 0 TO LEN_FIFO(SAMPLE)
      GET_FIFO SAMPLE, ATOD
      USING "UD<5><4>*  0.0.0.2.3"
      PRINT_USING #1, "<1Bh>A"; CHR$(9); CHR$(2); 5*ATOD; "      "
      WAIT_DURATION 250                    ' wait 0.25 sec
   NEXT

   PRINT #1, "<1Bh>A"; CHR$(8); CHR$(0); "<F0h>** DONE **  ";
   PRINT #1, "<1Bh>A"; CHR$(0); CHR$(3); "<F0h>Reset to Repeat Meas";
END
```

12.3 Appendix C: TIMERA Device Driver Frequency Range Tables

12.3.1 Range I

Factor	Frequency
200	12.500
201	12.438
202	12.376
203	12.315
204	12.255
205	12.195
206	12.136
207	12.077
208	12.019
209	11.962
210	11.905
211	11.848
212	11.792
213	11.737
214	11.682
215	11.628
216	11.574
217	11.521
218	11.468
219	11.416
220	11.364
221	11.312
222	11.261
223	11.211
224	11.161
225	11.111
226	11.062
227	11.013
228	10.965
229	10.917
230	10.870
231	10.823
232	10.776
233	10.730
234	10.684
235	10.638
236	10.593
237	10.549
238	10.504
239	10.460
240	10.417
241	10.373
242	10.331
243	10.288
244	10.246
245	10.204
246	10.163
247	10.121
248	10.081
249	10.040
250	10.000
251	9.960
252	9.920
253	9.881
254	9.842
255	9.803
0	9.765

12.3.2 RANGE 2

Factor	Frequency
50	12.500
51	12.255
52	12.019
53	11.792
54	11.574
55	11.364
56	11.161
57	10.965
58	10.776
59	10.593
60	10.417
61	10.246
62	10.081
63	9.920
64	9.765
65	9.615
66	9.469
67	9.328
68	9.191
69	9.057
70	8.928
71	8.802
72	8.680
73	8.561
74	8.445
75	8.333
76	8.223
77	8.116
78	8.012
79	7.911
80	7.812
81	7.716
82	7.621
83	7.530
84	7.440
85	7.352
86	7.267
87	7.183
88	7.102
89	7.022
90	6.944
91	6.868
92	6.793
93	6.720
94	6.648
95	6.578
96	6.510
97	6.443
98	6.377
99	6.313
100	6.250
101	6.188
102	6.127
103	6.067
104	6.009
105	5.952
106	5.896
107	5.841
108	5.787
109	5.733
110	5.681
111	5.630
112	5.580
113	5.530
114	5.482
115	5.434
116	5.387
117	5.341
118	5.296
119	5.252
120	5.208
121	5.165
122	5.122
123	5.081
124	5.040
125	5.000
126	4.960
127	4.921
128	4.882
129	4.844
130	4.807
131	4.770
132	4.734
133	4.699
134	4.664
135	4.629
136	4.595
137	4.562
138	4.528
139	4.496
140	4.464
141	4.432
142	4.401
143	4.370
144	4.340
145	4.310
146	4.280
147	4.251
148	4.222
149	4.194
150	4.166
151	4.139
152	4.111
153	4.084
154	4.058
155	4.032
156	4.006
157	3.980
158	3.955
159	3.930
160	3.906
161	3.881
162	3.858
163	3.834
164	3.810
165	3.787
166	3.765
167	3.742
168	3.720
169	3.698
170	3.676
171	3.654
172	3.633
173	3.612
174	3.591
175	3.571
176	3.551
177	3.531
178	3.511

Factor	Frequency
179	3.491
180	3.472
181	3.453
182	3.434
183	3.415
184	3.396
185	3.378
186	3.360
187	3.342
188	3.324
189	3.306
190	3.289
191	3.272
192	3.255
193	3.238
194	3.221
195	3.205
196	3.188
197	3.172
198	3.156
199	3.140
200	3.125
201	3.109
202	3.094
203	3.078
204	3.063
205	3.048
206	3.033
207	3.019
208	3.004
209	2.990
210	2.976
211	2.962
212	2.948
213	2.934
214	2.920
215	2.906
216	2.893
217	2.880
218	2.866
219	2.853
220	2.840
221	2.828
222	2.815
223	2.802
224	2.790
225	2.777
226	2.765
227	2.753
228	2.741
229	2.729
230	2.717
231	2.705
232	2.693
233	2.682
234	2.670
235	2.659
236	2.648
237	2.637
238	2.626
239	2.615
240	2.604
241	2.593
242	2.582
243	2.572
244	2.561
245	2.551
246	2.540
247	2.530
248	2.520
249	2.510
250	2.500
251	2.490
252	2.480
253	2.470
254	2.460
255	2.450
0	2.441

12.3.3 RANGE 3

Factor	Frequency
12	13.020
13	12.019
14	11.160
15	10.416
16	9.765
17	9.191
18	8.680
19	8.223
20	7.812
21	7.440
22	7.102
23	6.793
24	6.510
25	6.250
26	6.009
27	5.787
28	5.580
29	5.387
30	5.208
31	5.040
32	4.882
33	4.734
34	4.595
35	4.464
36	4.340
37	4.222
38	4.111
39	4.006
40	3.906
41	3.810
42	3.720
43	3.633
44	3.551
45	3.472
46	3.396
47	3.324
48	3.255
49	3.188
50	3.125
51	3.063
52	3.004
53	2.948
54	2.893
55	2.840
56	2.790
57	2.741
58	2.693
59	2.648
60	2.604
61	2.561
62	2.520
63	2.480
64	2.441
65	2.403
66	2.367
67	2.332
68	2.297
69	2.264
70	2.232
71	2.200
72	2.170
73	2.140
74	2.111
75	2.083
76	2.055
77	2.029
78	2.003
79	1.977
80	1.953
81	1.929
82	1.905
83	1.882
84	1.860
85	1.838
86	1.816
87	1.795
88	1.775
89	1.755
90	1.736
91	1.717
92	1.698
93	1.680
94	1.662
95	1.644
96	1.627
97	1.610
98	1.594
99	1.578
100	1.562
101	1.547
102	1.531
103	1.516
104	1.502
105	1.488
106	1.474
107	1.460
108	1.446
109	1.433
110	1.420
111	1.407
112	1.395
113	1.382
114	1.370
115	1.358
116	1.346
117	1.335
118	1.324
119	1.313
120	1.302
121	1.291
122	1.280
123	1.270
124	1.260
125	1.250
126	1.240
127	1.230
128	1.220
129	1.211
130	1.201
131	1.192
132	1.183
133	1.174
134	1.166
135	1.157
136	1.148
137	1.140
138	1.132
139	1.124
140	1.116
141	1.108
142	1.100
143	1.092

Factor	Frequency
144	1.085
145	1.077
146	1.070
147	1.062
148	1.055
149	1.048
150	1.041
151	1.034
152	1.027
153	1.021
154	1.014
155	1.008
156	1.001
157	995
158	988
159	982
160	976
161	970
162	964
163	958
164	952
165	946
166	941
167	935
168	930
169	924
170	919
171	913
172	908
173	903
174	897
175	892
176	887
177	882
178	877
179	872
180	868
181	863
182	858
183	853
184	849
185	844
186	840
187	835
188	831
189	826
190	822
191	818
192	813
193	809
194	805
195	801
196	797
197	793
198	789
199	785
200	781
201	777
202	773
203	769
204	765
205	762
206	758
207	754
208	751
209	747
210	744
211	740
212	737
213	733
214	730
215	726
216	723
217	720
218	716
219	713
220	710
221	707
222	703
223	700
224	697
225	694
226	691
227	688
228	685
229	682
230	679
231	676
232	673
233	670
234	667
235	664
236	662
237	659
238	656
239	653
240	651
241	648
242	645
243	643
244	640
245	637
246	635
247	632
248	630
249	627
250	625
251	622
252	620
253	617
254	615
255	612
0	610

12.4 APPENDIX D: DATASHEETS

ECONO-Tiger™

High Speed Multitasking Computers

Wilke Techno Logy

Data Sheet

Tiny, high speed multitasking computers in the size of a component. ECONO Tigers™ are universal, full featured control computers used in numerous projects and series products as:

- GPS systems + traffic control
- Medical instruments
- Security applications + access control
- Vending machines
- Communication equipment
- Industrial control
- Point of sales applications
- Power plants ... and many more

ECONO Tigers™ offer

- Shortest development cycles
- Highest product reliability
- Low cost
- Innovative, additional features

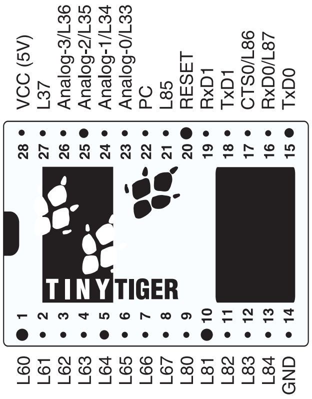
For further information, detailed literature and manuals in printed or downloadable formats visit:

www.wilke.de

or

www.wilke-technology.com

544 kB to 1 MB FLASH + SRAM



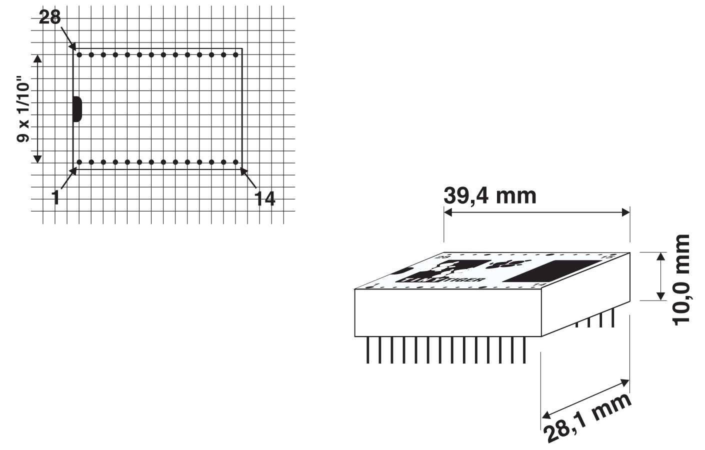
ENN-R/4, ENN-1/4, ENN-4/4

◆ Dimensions:	approx. 28.1 x 39.4 x 10.0 mm / 1.11 x 1.55 x 0.39“ 28-pin DIP type case pin to pin clearance 2.54 mm / 0.1“, row distance 22.86 mm / 0.9“ square pins 0.64 x 0.64 mm / 0.025 x 0.025“
◆ Weight:	approx. 20g / 0.7 ounces
◆ Operating temperature:	
Standard:	0°C to +70°C
Expanded:	expanded temperature ranges on request
◆ Power supply:	4.6V - 5.5V / 45-60 mA typ.
◆ System timebase accuracy:	+/-50 ppm base tolerance, +/-30 ppm over temp. range -20°C to +70°C +/-5 ppm per year max. aging Other specifications available optional
◆ Reset:	Power-ON reset internal, active @Vcc = 4,5V +/- 0.1V Reset input: LOW-active, internal pull-up R = 10 KΩ typ.
◆ I/O pins:	24 universal I/O-pins

Max current for digital outputs:	1.6 mA / pin (low, U=0.45V max) -0.4 mA / pin (high, U=2.4V min) Max. darlington driver current: -3,5 mA (U=1.5V), max 8 pins
Rising time / falling time:	15 ns typ. (10%, 90%)
Impedance digital Inputs:	High-Impedance or additional pull-up resistor: L33 ... L37 pull-up 50 ... 150 kΩ L41 pull-up 50 ... 150 kΩ L60 ... L67 pull-up 50 ... 150 kΩ L80...L87 pull-up 50 ... 150 kΩ L90...L94 pull-up 50 ... 150 kΩ
Digital Inputs:	Input voltage „high“: 0.7 * Vcc min Input voltage „low“: 0.8V max
Analog input:	4 channels
Vref analog inputs:	Vcc internal
Impedance analog inputs:	20 kΩ typ., note: low impedance in power down state
Analog input range:	0...Vcc
Analog input resolution:	10 bit internal hardware resolution, 12 bit through moving window integration. Linearisation and calibration through software function LIN_APPROX and flash calibration tables.
Analog input accuracy:	+/- 0.5 LSB quantize error +/- 1.5 LSB typ, +/- 4 LSB max at normal speed (-20°C ... 70°C) +/- 4.0 LSB typ, +/- 8 LSB max in high speed (-20°C ... 70°C)
Analog sampling rate:	up to 50,000 samples / sec
Analog sampling buffer:	up to 30 kByte
Memory internal:	32 KB ... 512 KB Static RAM 512 KB FLASH
Serial channels:	2 buffered UART channels: CH-0: RxD, TxD, CTS Baudrates: 300,600,1200, 2400, 4800, 9600, 19200, 38400, 76800, 153600, 614400 Data/Parity: 7N, 7E, 7O, 8N, 8E, 8O, 9N Buffer sizes: 256, 512, 1024, 2048, 4096 Bytes CH-1: as above, RxD and TxD lines Level systems: 5V TTL levels Up to 8 additional serial I/O channels through software driver SER2.TDD. Selectable: RxD, TxD or RxD + TxD per channel Max baudrate (1 channel): 9600 Bd TxD, 4800 Bd RxD Max baudrate multi channel: -> divided by no of channels
Pulses:	Resolutions: 0.4 / 1.6 / 6.4 / 50 µs

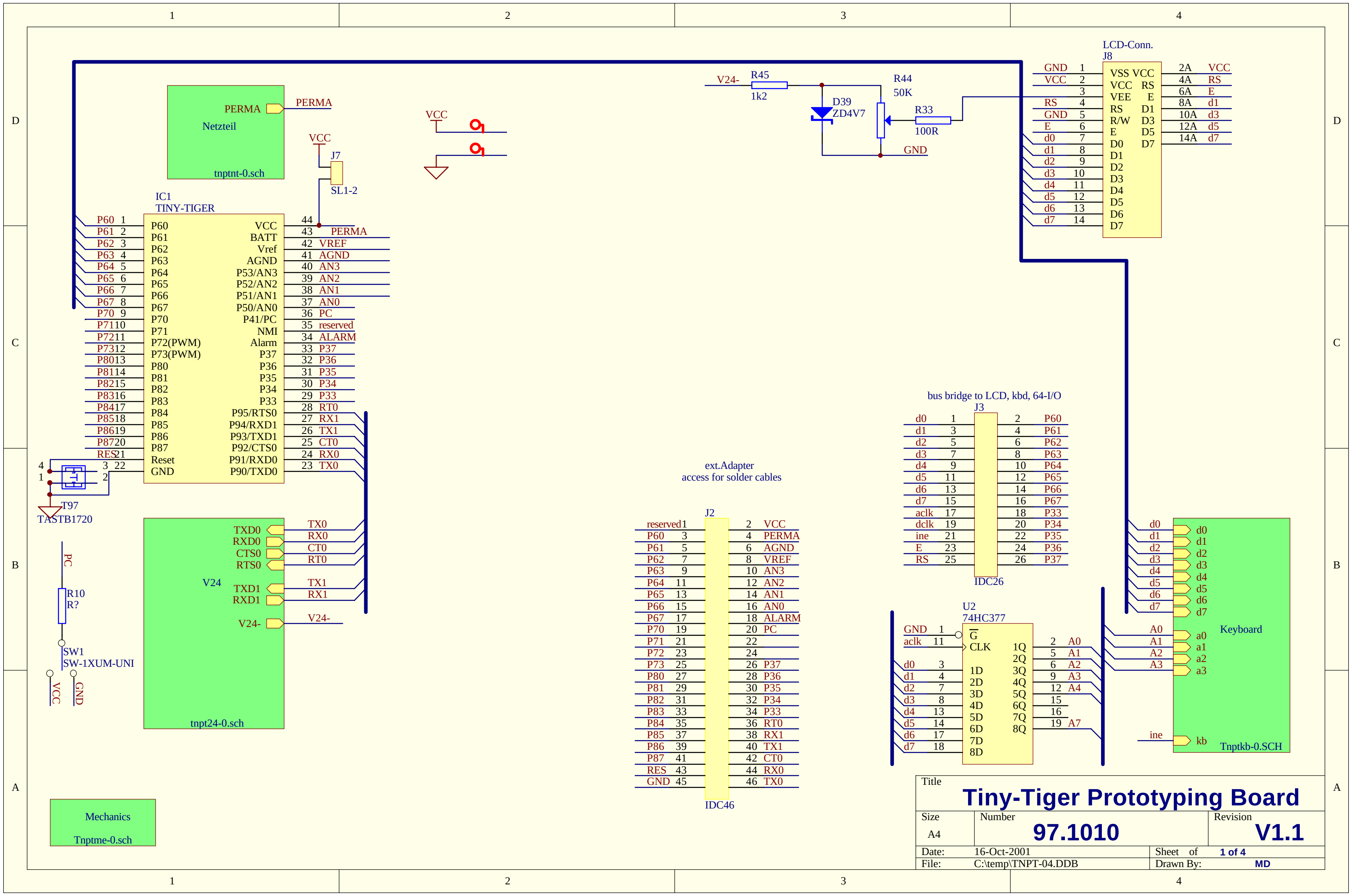
ECONO-Tiger™

High Speed Multitasking Computers



ECONO Tiger™ Computer Modules:

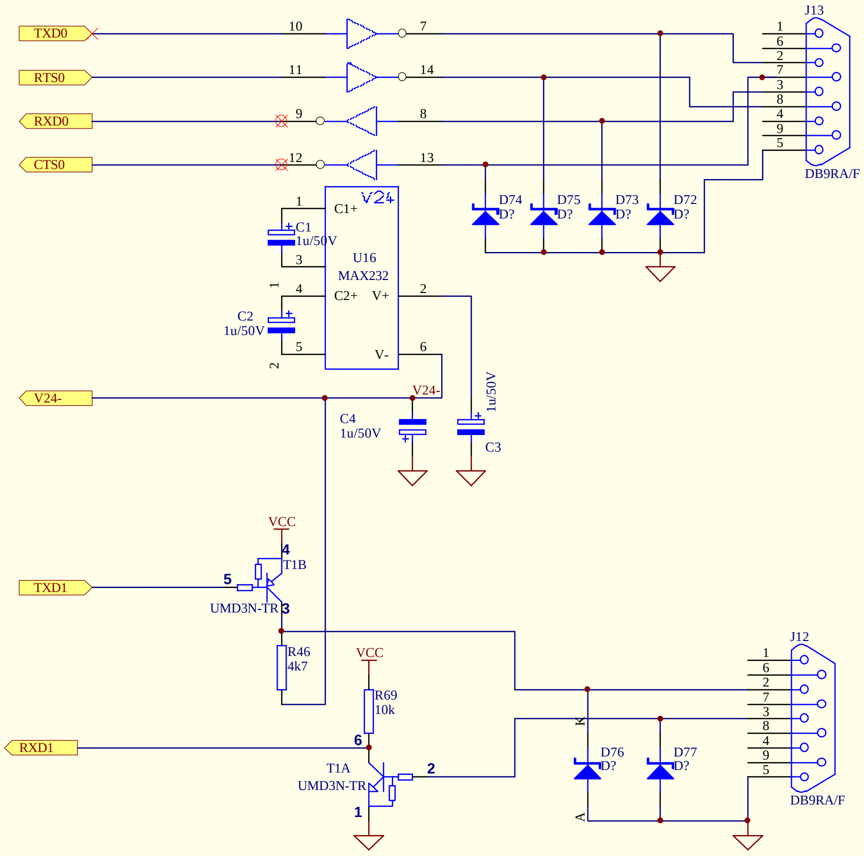
Type	SRAM	FLASH	Serial	Realtime Clock
ENN-R/4	32 KByte	512 KByte	5V	-
ENN-1/4	128 KByte	512 KByte	5V	-
ENN-4/4	512 KByte	512 KByte	5V	-



Title
Tiny-Tiger Prototyping Board

Size	Number	Revision
A4	**97.1010**	**V1.1**

Date: 16-Oct-2001
Sheet 1 of 4
File: C:\temp\TNPT-04.DDB
Drawn By: MD



Title

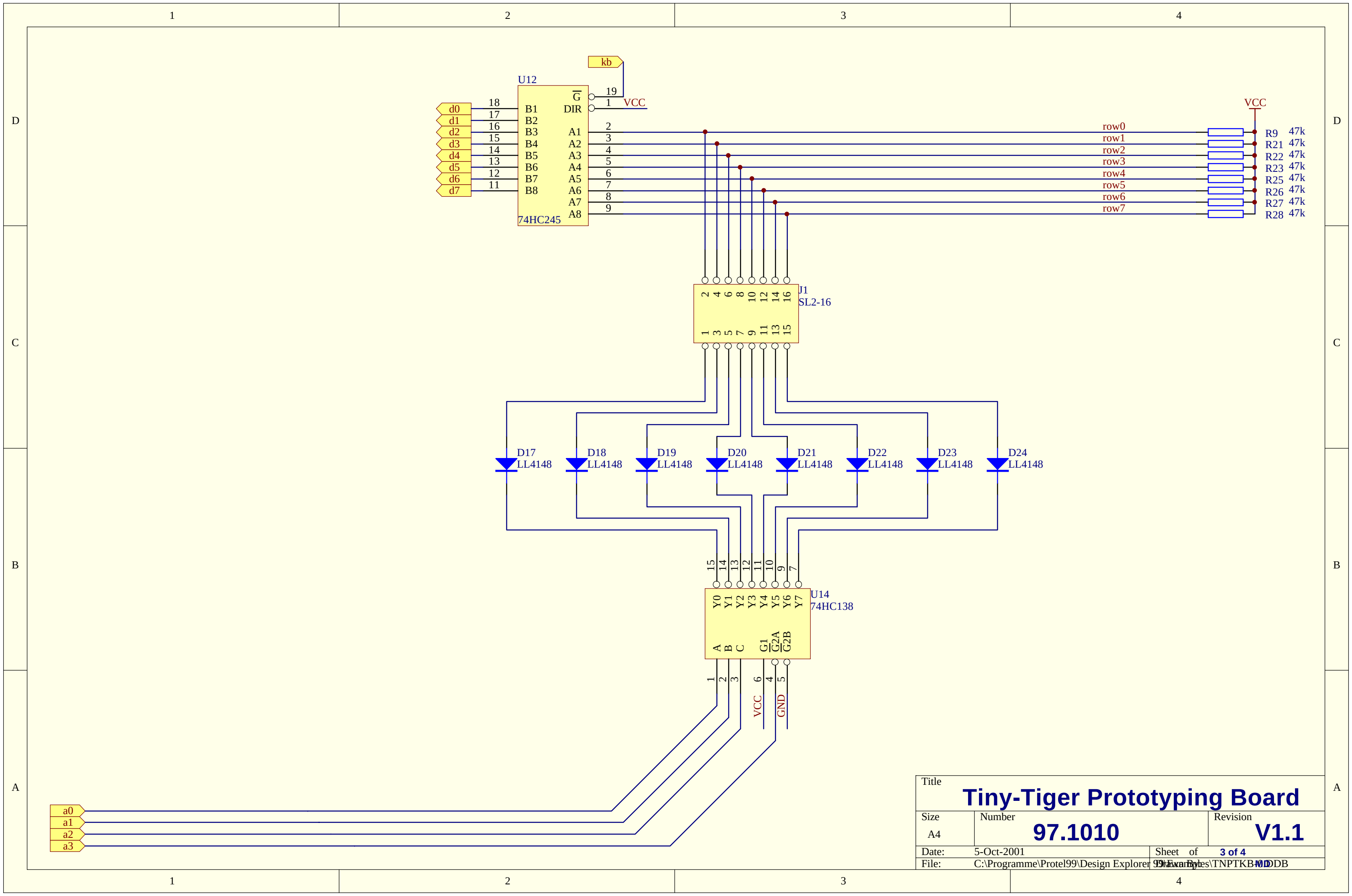
Tiny-Tiger Prototyping Board

Size
A4

Number
97.1010

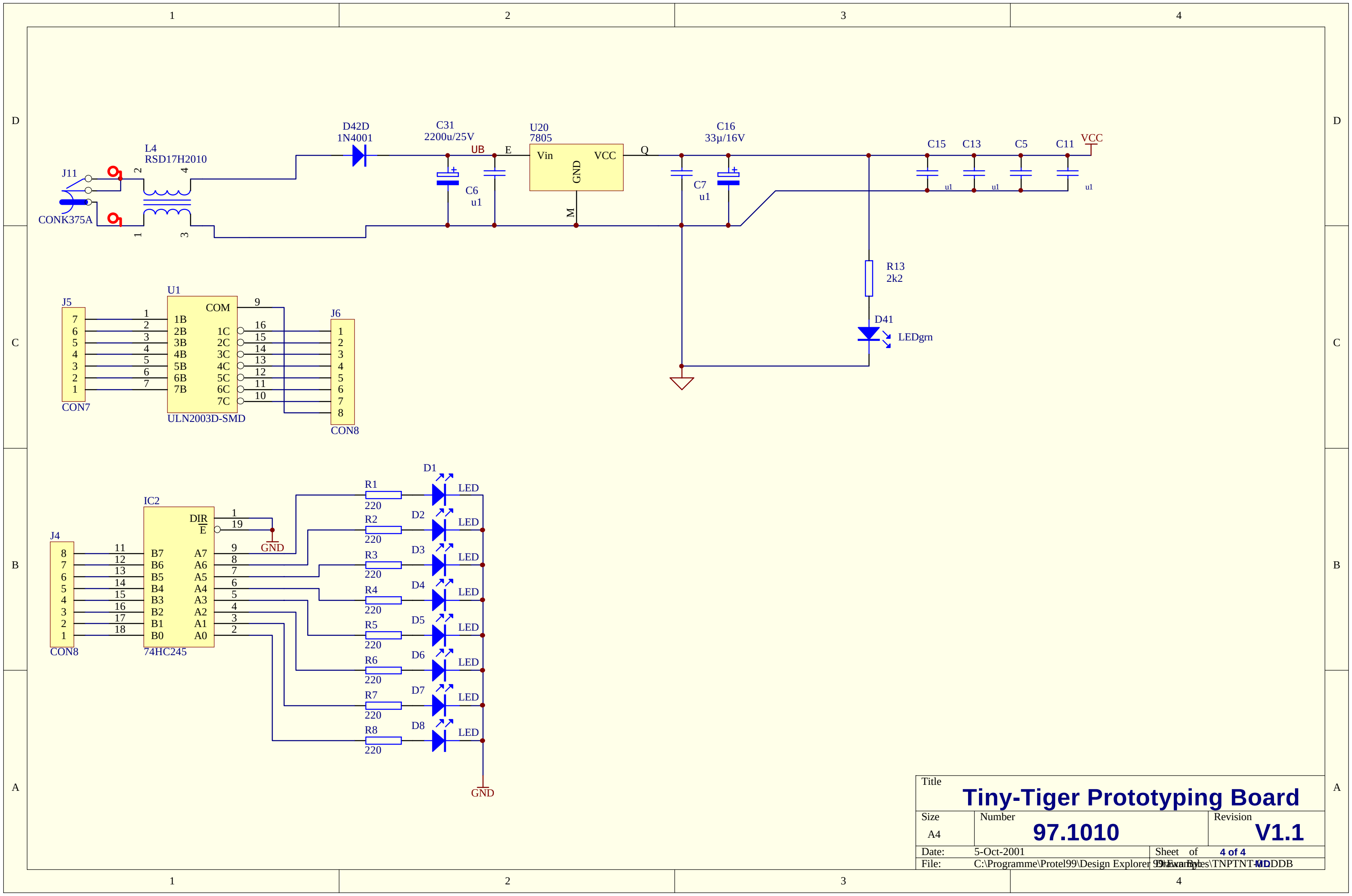
Revision
V1.1

Date: 5-Oct-2001
Sheet of **2 of 4**
File: C:\Programme\Protel99\Design Explorer 99\Examples\TNPT24-MDDB
Drawn By:



Title
Tiny-Tiger Prototyping Board

Size: A4
Number: **97.1010**
Revision: **V1.1**
Date: 5-Oct-2001
Sheet of: 3 of 4
File: C:\Programme\Protel99\Design Explorer 99\Examples\TNPTKB.DDB
Drawn By: MD



Title
Tiny-Tiger Prototyping Board

Size	Number	Revision
A4	**97.1010**	**V1.1**

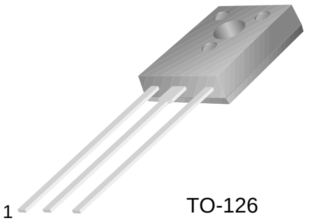
Date: 5-Oct-2001
Sheet of **4 of 4**
File: C:\Programme\Protel99\Design Explorer 99\Examples\TNPTNT-01.DDB
Drawn By: **MD**

FAIRCHILD
SEMICONDUCTOR TM

BD675A/677A/679A/681

Medium Power Linear and Switching Applications

- Medium Power Darlington TR
- Complement to BD676A, BD678A, BD680A and BD682 respectively



TO-126

1. Emitter 2.Collector 3.Base

NPN Epitaxial Silicon Transistor

Absolute Maximum Ratings T_C=25°C unless otherwise noted

Symbol	Parameter		Value	Units
V_{CBO}	Collector-Base Voltage	: BD675A	45	V
		: BD677A	60	V
		: BD679A	80	V
		: BD681	100	V
V_{CEO}	Collector-Emitter Voltage	: BD675A	45	V
		: BD677A	60	V
		: BD679A	80	V
		: BD681	100	V
V_{EBO}	Emitter-Base Voltage		5	V
I_C	Collector Current (DC)		4	A
I_{CP}	*Collector Current (Pulse)		6	A
I_B	Base Current		100	mA
P_C	Collector Dissipation (T_C=25°C)		40	W
T_J	Junction Temperature		150	°C
T_{STG}	Storage Temperature		- 65 ~ 150	°C

Electrical Characteristics T_C=25°C unless otherwise noted

Symbol	Parameter		Test Condition	Min.	Typ.	Max.	Units
V_{CEO}(sus)	*Collector-Emitter Sustaining Voltage						
		: BD675A	I_C = 50mA, I_B = 0	45			V
		: BD677A		60			V
		: BD679A		80			V
		: BD681		100			V
I_{CBO}	Collector-Base Voltage	: BD675A	V_{CB} = 45V, I_E = 0			200	µA
		: BD677A	V_{CB} = 60V, I_E = 0			200	µA
		: BD679A	V_{CB} = 80V, I_E = 0			200	µA
		: BD681	V_{CB} = 100V, V_{BE} = 0			200	µA
I_{CEO}	Collector Cut-off Current	: BD675A	V_{CE} = 45V, V_{BE} = 0			500	µA
		: BD677A	V_{CE} = 60V, V_{BE} = 0			500	µA
		: BD679A	V_{CE} = 80V, V_{BE} = 0			500	µA
		: BD681	V_{CE} = 100V, V_{BE} = 0			500	µA
I_{EBO}	Emitter Cut-off Current		V_{EB} = 5V, I_C = 0			2	mA
h_{FE}	* DC Current Gain	: BD675A/677A/679A	V_{CE} = 3V, I_C = 2A	750			
		: BD681	V_{CE} = 3V, I_C = 1.5A	750			
V_{CE}(sat)	* Collector-Emitter Saturation Voltage						
		: BD675A/677A/679A	I_C = 2A, I_B = 40mA			2.8	V
		: BD681	I_C = 1.5A, I_B = 30mA			2.5	V
V_{BE}(on)	* Base-Emitter ON Voltage	: BD675A/677A/679A	V_{CE} = 3V, I_C = 2A			2.5	V
		: BD681	V_{CE} = 3V, I_C = 1.5A			2.5	V

* Pulse Test: PW=300µs, duty Cycle=1.5% Pulsed

Typical Characteristics

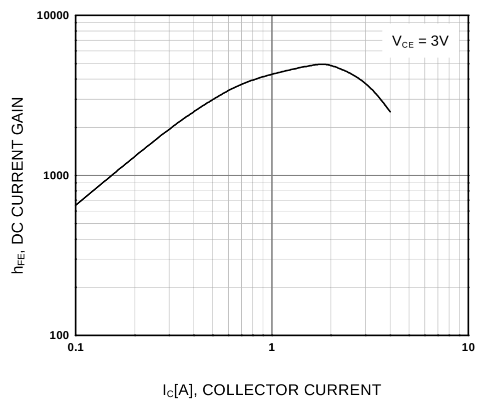


Figure 1. DC current Gain

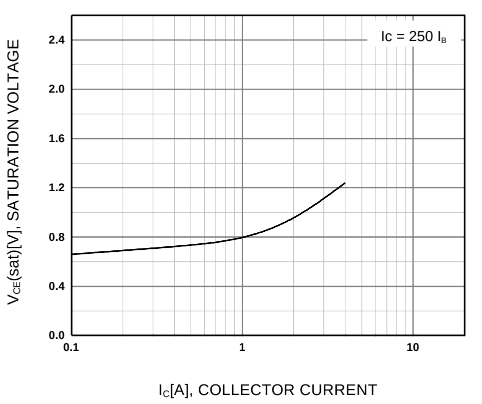


Figure 2. Collector-Emitter Saturation Voltage

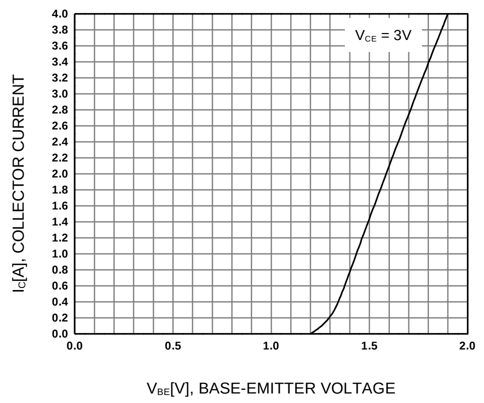


Figure 3. Base-Emitter On Voltage

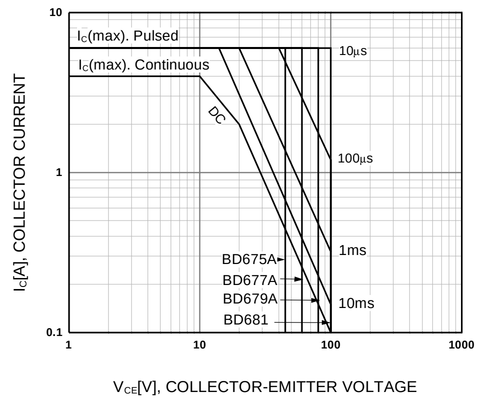


Figure 4. Safe Operating Area

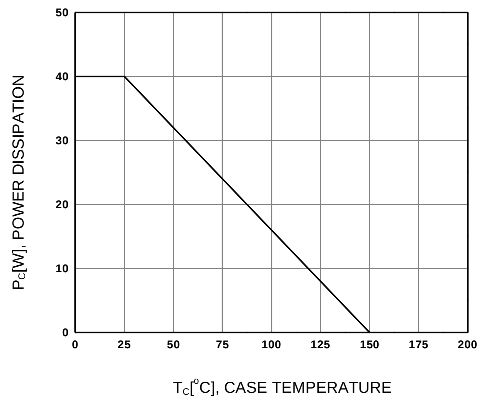
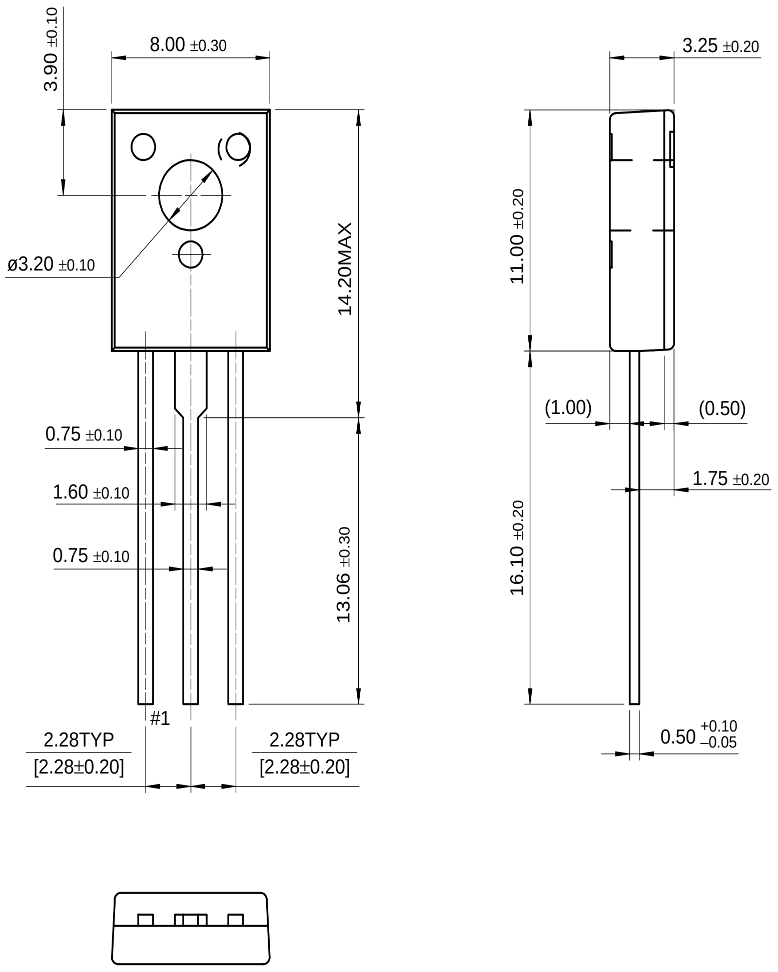


Figure 5. Power Derating

Package Demensions

TO-126



Dimensions in Millimeters

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HiSeC™
ISOPLANAR™
MICROWIRE™
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PowerTrench®
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SuperSOT™-6
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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

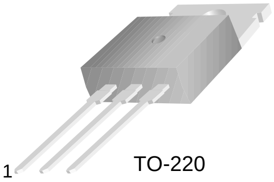
Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

FAIRCHILD
SEMICONDUCTOR ™

BDW93/A/B/C

Hammer Drivers, Audio Amplifiers Applications

- Power Darlington TR
- Complement to BDW94, BDW94A, BDW94B and BDW94C respectively



TO-220

1.Base 2.Collector 3.Emitter

NPN Epitaxial Silicon Transistor

Absolute Maximum Ratings T_C=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector-Base Voltage		
	: BDW93	45	V
	: BDW93A	60	V
	: BDW93B	80	V
	: BDW93C	100	V
V_{CEO}	Collector-Emitter Voltage		
	: BDW93	45	V
	: BDW93A	60	V
	: BDW93B	80	V
	: BDW93C	100	V
I_C	Collector Current (DC)	12	A
I_{CP}	*Collector Current (Pulse)	15	A
I_B	Base Current	0.2	A
P_C	Collector Dissipation (T_C=25°C)	80	W
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	- 65 ~ 150	°C

Thermal Characteristics T_C=25°C unless otherwise noted

Symbol	Parameter		Value	Units
$R_{\theta jc}$	Thermal Resistance	Junction to Case	1.5	°C/W

Electrical Characteristics T_C=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Typ.	Max.	Units
BV_{CEO}(sus)	* Collector-Emitter Sustaining Voltage : BDW93 : BDW93A : BDW93B : BDW93C	I_C = 100mA, I_B = 0	 45 60 80 100			 V V V V
I_{CBO}	Collector Cut-off Current : BDW93 : BDW93A : BDW93B : BDW93C	 V_{CB} = 45V, I_E = 0 V_{CB} = 60V, I_E = 0 V_{CB} = 80V, I_E = 0 V_{CB} = 100V, I_E = 0			 100 100 100 100	 µA µA µA µA
I_{CEO}	Collector Cut-off Current : BDW93 : BDW93A : BDW93B : BDW93C	 V_{CE} = 45V, I_B = 0 V_{CE} = 60V, I_B = 0 V_{CE} = 80V, I_B = 0 V_{CE} = 100V, I_B = 0			 1 1 1 1	 mA mA mA mA
I_{EBO}	Emitter Cut-off Current	V_{EB} = 5V, I_C = 0			2	mA
h_{FE}	* DC Current Gain	V_{CE} = 3V, I_C = 3A V_{CE} = 3V, I_C = 5A V_{CE} = 3V, I_C = 10A	1000 750 100		 20000	
V_{CE}(sat)	* Collector-Emitter Saturation Voltage	I_C = 5A, I_B = 20mA I_C = 10A, I_B = 100mA			2 3	V V
V_{BE}(sat)	* Base-Emitter Saturation Voltage	I_C = 5A, I_B = 20mA I_C = 10A, I_B = 100mA			2.5 4	V V
V_F	* Parallel Diode Forward Voltage	I_F = 5A I_F = 10A		1.3 1.8	2 4	V V

* Pulse Test: PW=300µs, duty Cycle =1.5% Pulsed

Typical characteristics

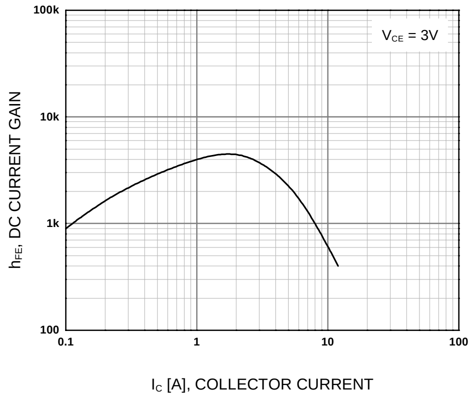


Figure 1. DC Current Gain

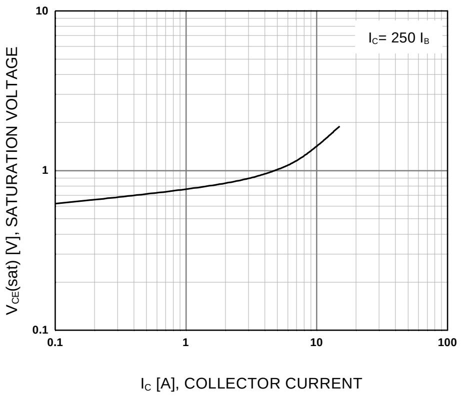


Figure 2. Collector-Emitter Saturation Voltage

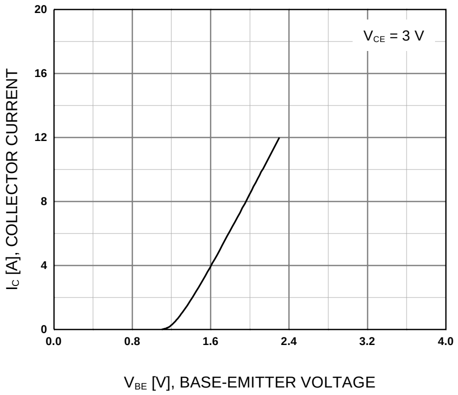


Figure 3. Base-Emitter On Voltage

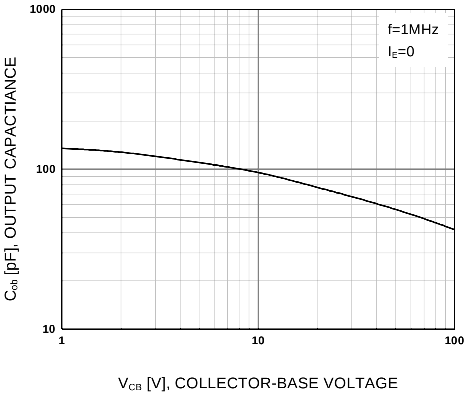


Figure 4. Collector Output Capacitance

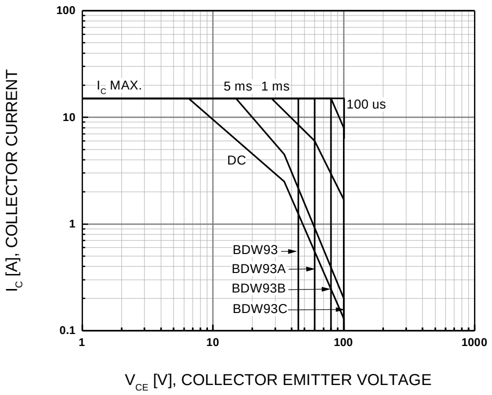


Figure 5. Safe Operating Area

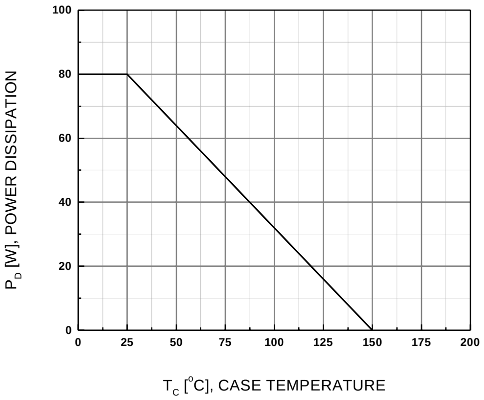
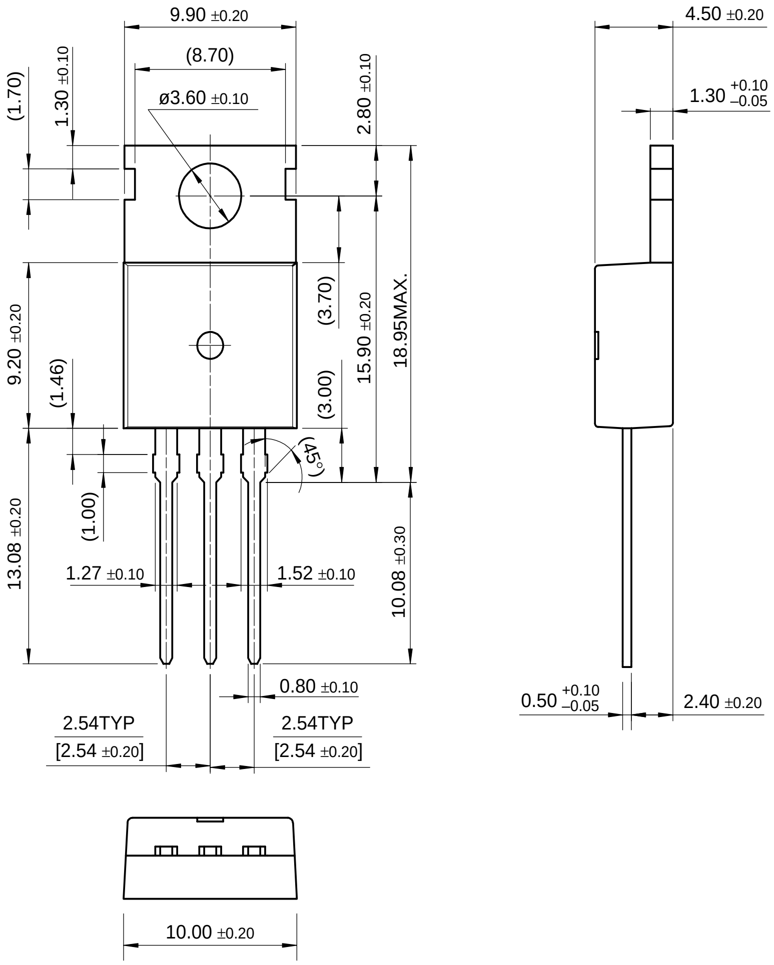


Figure 6. Power Derating

Package Demensions

TO-220



Dimensions in Millimeters

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Bottomless™
CoolFET™
CROSSVOLT™
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FACT™
FACT Quiet Series™
FAST®
FASTr™
GTO™
HiSeC™
ISOPLANAR™
MICROWIRE™
POP™
PowerTrench®
QFET™
QS™
Quiet Series™
SuperSOT™-3
SuperSOT™-6
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UHC™
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As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, or (c) whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in significant injury to the user.

2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

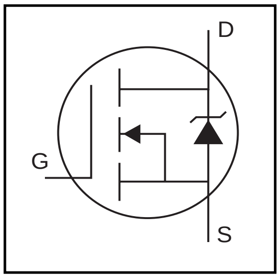
International
IOR Rectifier

PD - 94006

IRF640N
IRF640NS
IRF640NL

HEXFET® Power MOSFET

- Advanced Process Technology
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated
- Ease of Paralleling
- Simple Drive Requirements



V_{DSS} = 200V

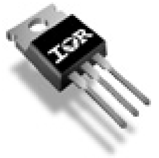
$R_{DS(on)}$ = 0.15Ω

I_D = 18A

Description

Fifth Generation HEXFET® Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET Power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.
The D^2Pak is a surface mount power package capable of accommodating die sizes up to HEX-4. It provides the highest power capability and the lowest possible on-resistance in any existing surface mount package. The D^2Pak is suitable for high current applications because of its low internal connection resistance and can dissipate up to 2.0W in a typical surface mount application.
The through-hole version (IRF640NL) is available for low-profile application.



TO-220AB
IRF640N

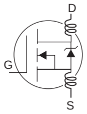
D^2Pak
IRF640NS

TO-262
IRF640NL

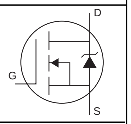
Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	18	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	13	
I_{DM}	Pulsed Drain Current ①	72	
P_D @T_C = 25°C	Power Dissipation	150	W
	Linear Derating Factor	1.0	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
E_{AS}	Single Pulse Avalanche Energy②	247	mJ
I_{AR}	Avalanche Current①	18	A
E_{AR}	Repetitive Avalanche Energy①	15	mJ
dv/dt	Peak Diode Recovery dv/dt ⑥	8.1	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +175	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 srew④	10 lbf•in (1.1N•m)	

Electrical Characteristics @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	200	—	—	V	V_{GS} = 0V, I_D = 250μA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.25	—	V/°C	Reference to 25°C, I_D = 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	0.15	Ω	V_{GS} = 10V, I_D = 11A ③
$V_{GS(th)}$	Gate Threshold Voltage	2.0	—	4.0	V	V_{DS} = V_{GS}, I_D = 250μA
g_{fs}	Forward Transconductance	6.8	—	—	S	V_{DS} = 50V, I_D = 11A ③
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	μA	V_{DS} = 200V, V_{GS} = 0V
		—	—	250		V_{DS} = 160V, V_{GS} = 0V, T_J = 150°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	V_{GS} = 20V
	Gate-to-Source Reverse Leakage	—	—	-100		V_{GS} = -20V
Q_g	Total Gate Charge	—	—	67	nC	I_D = 11A
Q_{gs}	Gate-to-Source Charge	—	—	11		V_{DS} = 160V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	33		V_{GS} = 10V, See Fig. 6 and 13
$t_{d(on)}$	Turn-On Delay Time	—	10	—	ns	V_{DD} = 100V
t_r	Rise Time	—	19	—		I_D = 11A
$t_{d(off)}$	Turn-Off Delay Time	—	23	—		R_G = 2.5Ω
t_f	Fall Time	—	5.5	—		R_D = 9.0Ω, See Fig. 10 ③
L_D	Internal Drain Inductance	—	4.5	—	nH	Between lead, 6mm (0.25in.) from package and center of die contact 
L_S	Internal Source Inductance	—	7.5	—		
C_{iss}	Input Capacitance	—	1160	—	pF	V_{GS} = 0V
C_{oss}	Output Capacitance	—	185	—		V_{DS} = 25V
C_{rss}	Reverse Transfer Capacitance	—	53	—		ƒ = 1.0MHz, See Fig. 5

Source-Drain Ratings and Characteristics

	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—	—	18	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode)①	—	—	72		
V_{SD}	Diode Forward Voltage	—	—	1.3	V	T_J = 25°C, I_S = 11A, V_{GS} = 0V ③
t_{rr}	Reverse Recovery Time	—	167	251	ns	T_J = 25°C, I_F = 11A
Q_{rr}	Reverse Recovery Charge	—	929	1394	nC	di/dt = 100A/μs ③
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by L_S+L_D)				

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	1.0	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface ④	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient④	—	62	
$R_{\theta JA}$	Junction-to-Ambient (PCB mount)⑤	—	40	

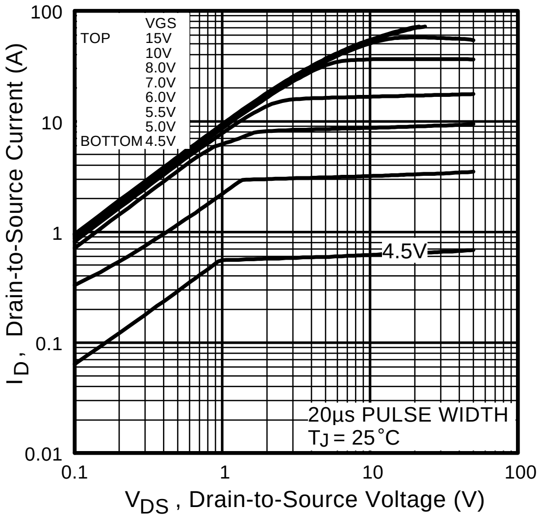


Fig 1. Typical Output Characteristics

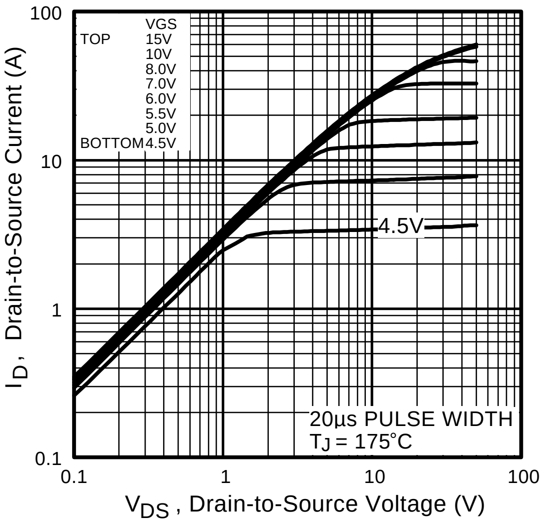


Fig 2. Typical Output Characteristics

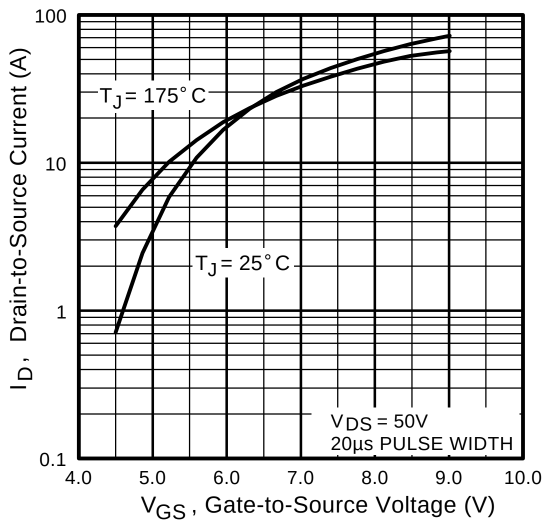


Fig 3. Typical Transfer Characteristics

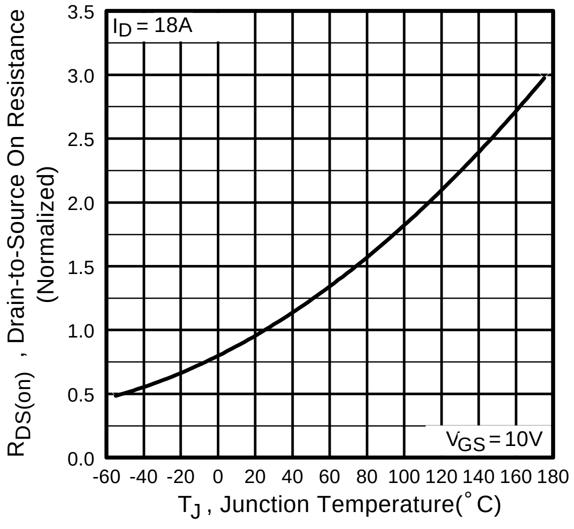


Fig 4. Normalized On-Resistance
Vs. Temperature

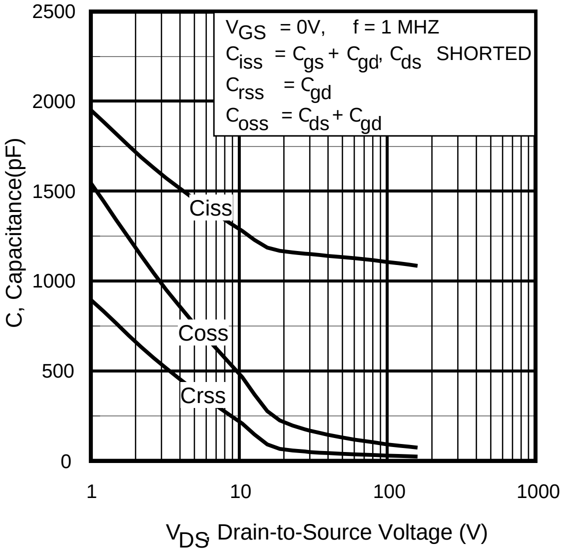


Fig 5. Typical Capacitance Vs. Drain-to-Source Voltage

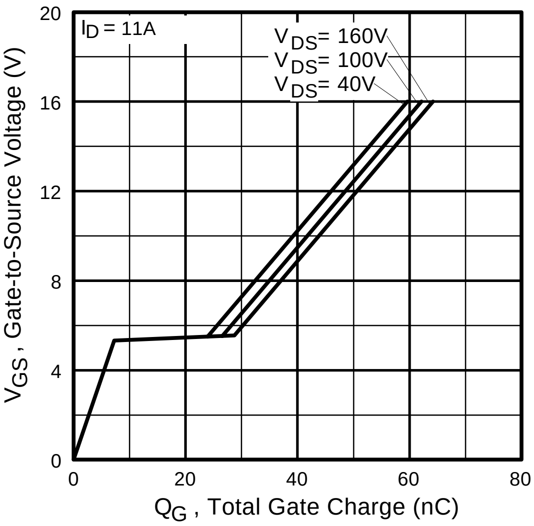


Fig 6. Typical Gate Charge Vs. Gate-to-Source Voltage

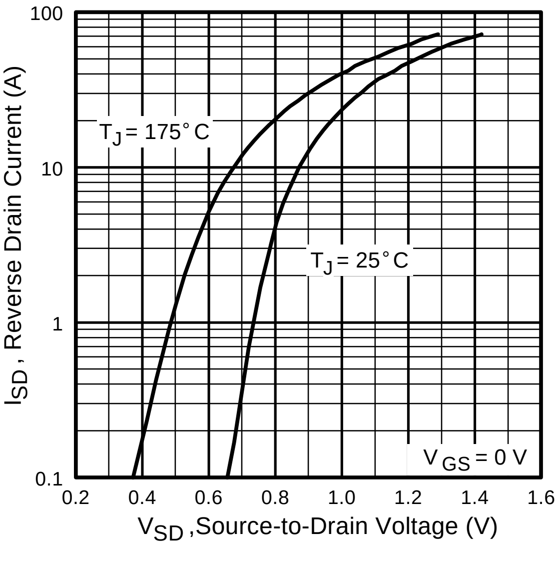


Fig 7. Typical Source-Drain Diode Forward Voltage

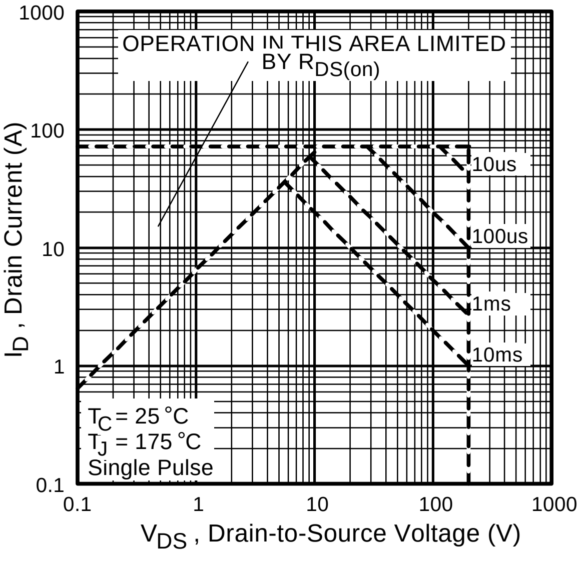


Fig 8. Maximum Safe Operating Area

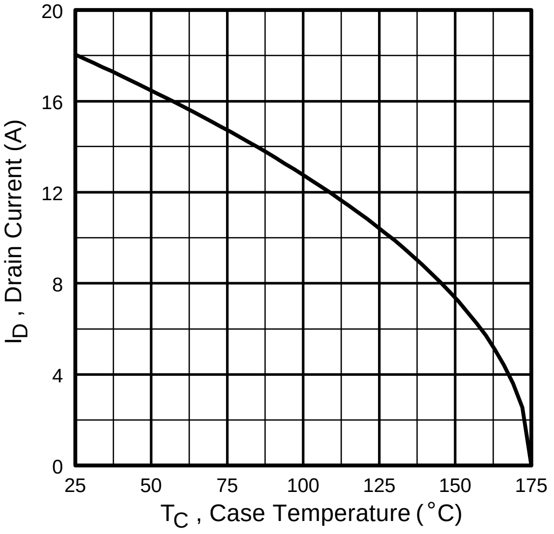


Fig 9. Maximum Drain Current Vs. Case Temperature

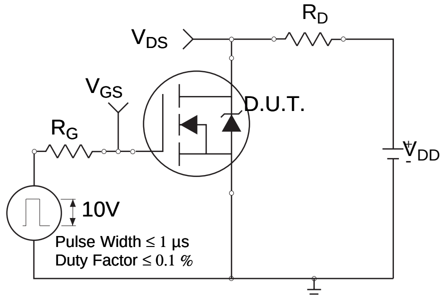


Fig 10a. Switching Time Test Circuit

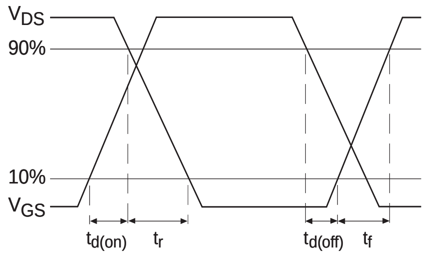


Fig 10b. Switching Time Waveforms

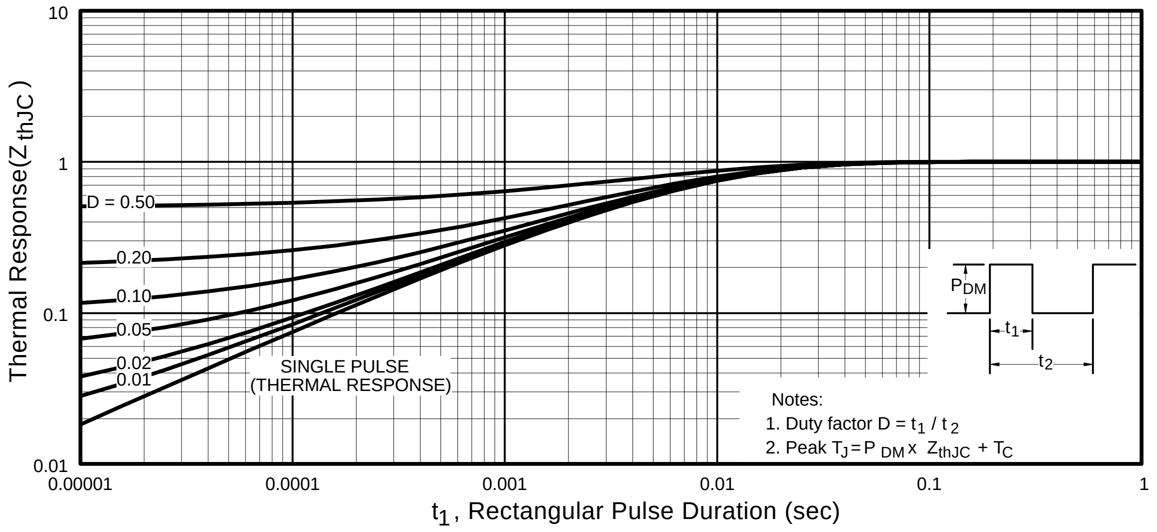


Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

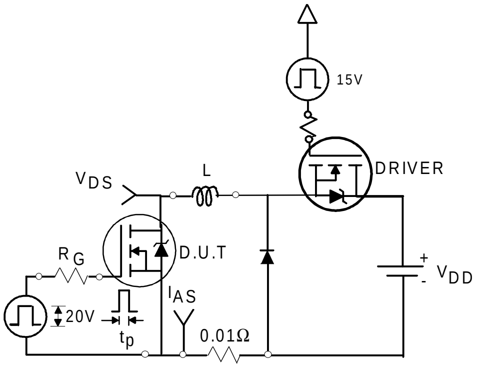


Fig 12a. Unclamped Inductive Test Circuit

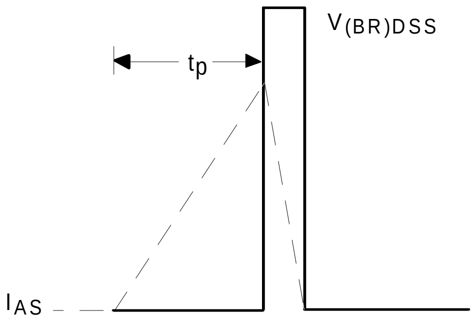


Fig 12b. Unclamped Inductive Waveforms

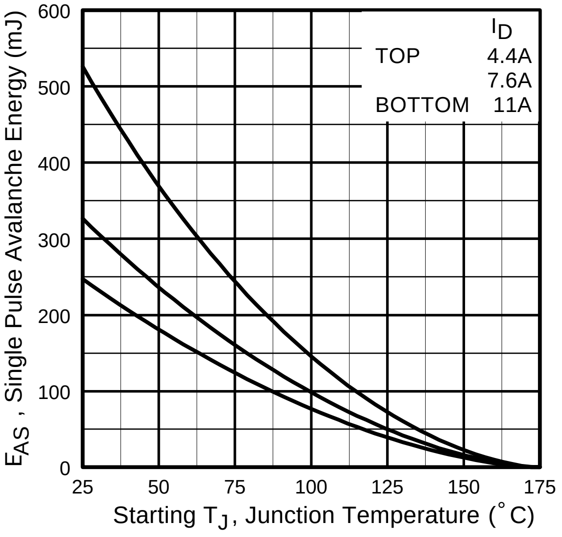


Fig 12c. Maximum Avalanche Energy Vs. Drain Current

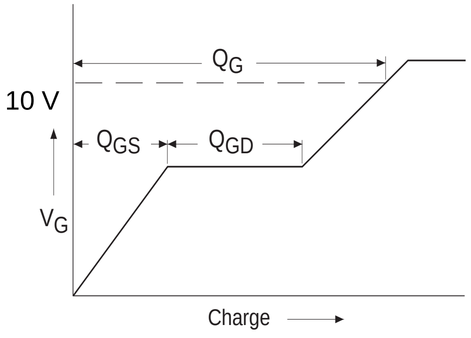


Fig 13a. Basic Gate Charge Waveform

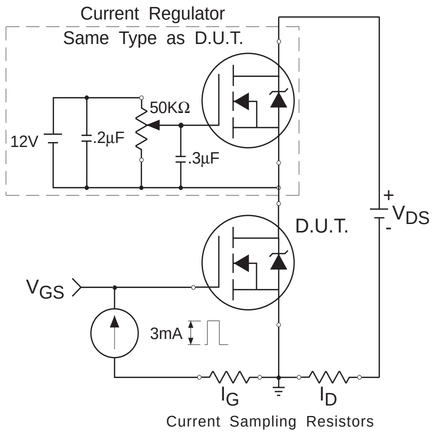
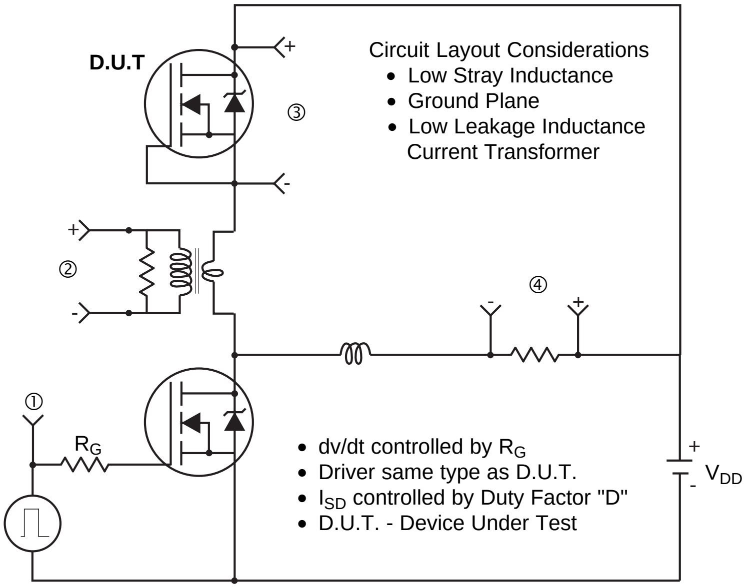


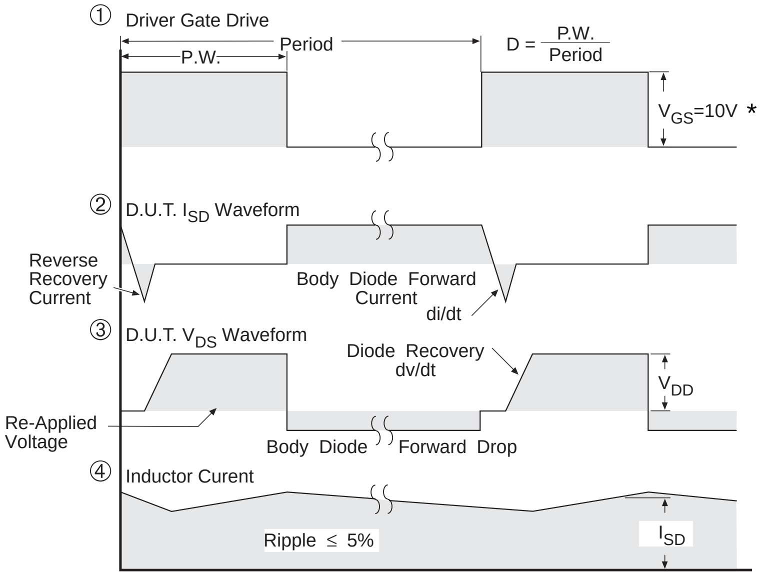
Fig 13b. Gate Charge Test Circuit

Peak Diode Recovery dv/dt Test Circuit



Circuit Layout Considerations
- Low Stray Inductance
- Ground Plane
- Low Leakage Inductance Current Transformer

- dv/dt controlled by R_G
- Driver same type as D.U.T.
- I_{SD} controlled by Duty Factor "D"
- D.U.T. - Device Under Test

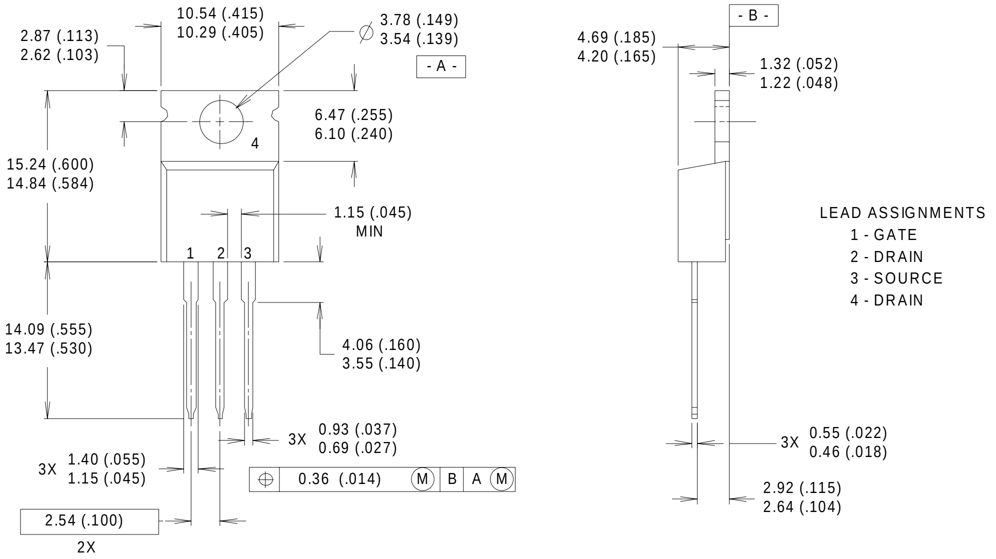


* V_{GS} = 5V for Logic Level Devices

Fig 14. For N-Channel HEXFET® Power MOSFETs

TO-220AB Package Outline

Dimensions are shown in millimeters (inches)

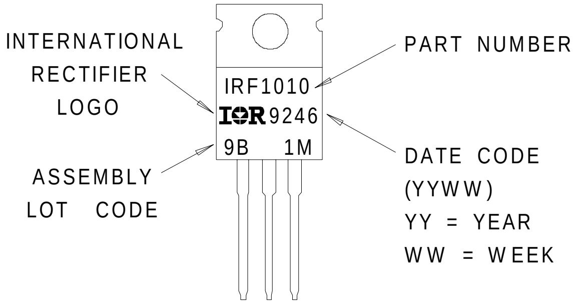


NOTES:

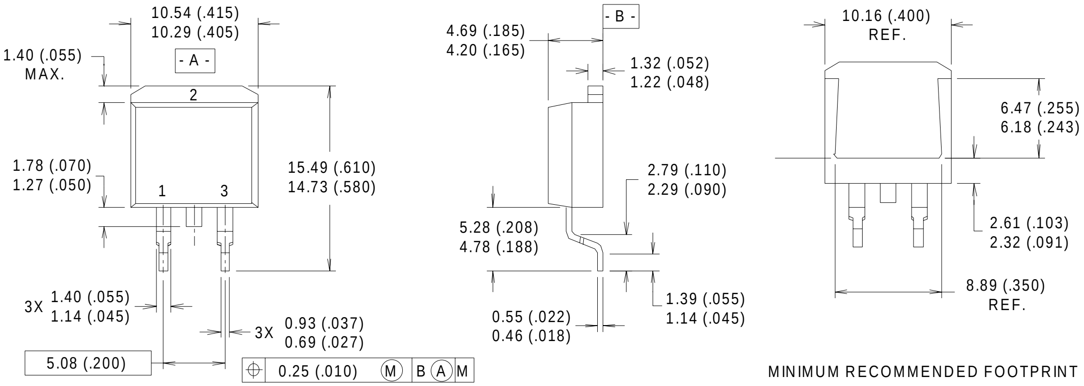
1 DIMENSIONING & TOLERANCING PER ANSI Y14.5M, 1982.
2 CONTROLLING DIMENSION : INCH
3 OUTLINE CONFORMS TO JEDEC OUTLINE TO-220AB.
4 HEATSINK & LEAD MEASUREMENTS DO NOT INCLUDE BURRS.

TO-220AB Part Marking Information

EXAMPLE : THIS IS AN IRF1010
WITH ASSEMBLY
LOT CODE 9B1M

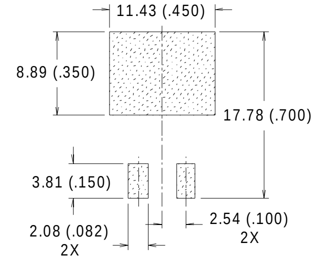


D^{2}Pak Package Outline

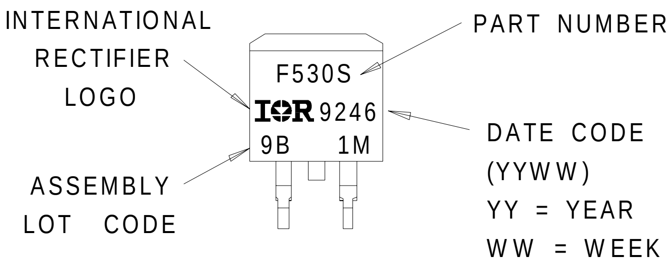


NOTES:
1 DIMENSIONS AFTER SOLDER DIP.
2 DIMENSIONING & TOLERANCING PER ANSI Y14.5M, 1982.
3 CONTROLLING DIMENSION : INCH.
4 HEATSINK & LEAD DIMENSIONS DO NOT INCLUDE BURRS.

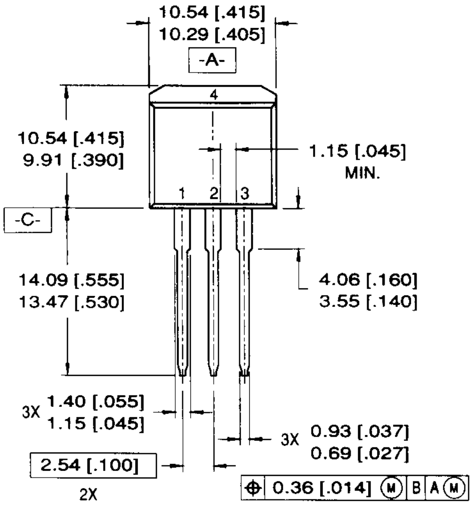
LEAD ASSIGNMENTS
1 - GATE
2 - DRAIN
3 - SOURCE

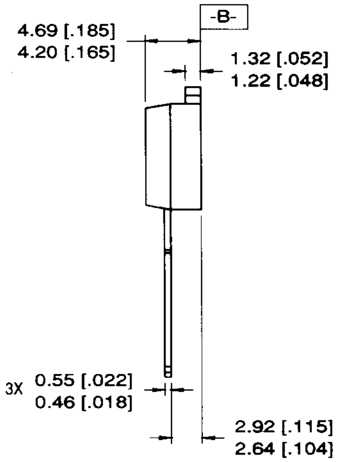


D^{2}Pak Part Marking Information



TO-262 Package Outline





LEAD ASSIGNMENTS

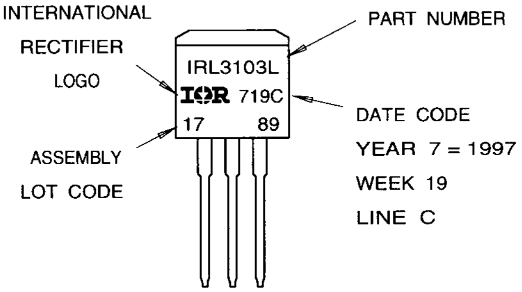
1 = GATE
2 = DRAIN
3 = SOURCE
4 = DRAIN

NOTES:

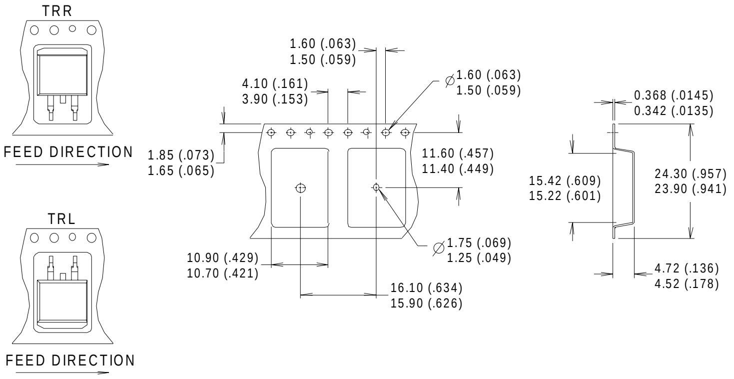
1. DIMENSIONING & TOLERANCING PER ANSI Y14.5M-1982
2. CONTROLLING DIMENSION: INCH.
3. DIMENSIONS ARE SHOWN IN MILLIMETERS [INCHES].
4. HEATSINK & LEAD DIMENSIONS DO NOT INCLUDE BURRS.

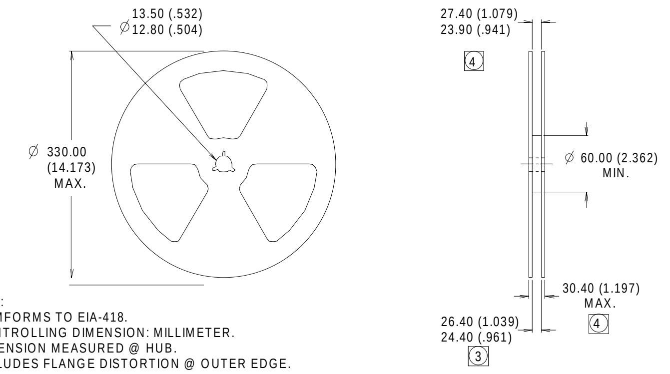
TO-262 Part Marking Information

EXAMPLE: THIS IS AN IRL3103L
LOT CODE 1789
ASSEMBLED ON WW 19, 1997
IN THE ASSEMBLY LINE "C"



D^2Pak Tape & Reel Information





NOTES :
1. COMFORMS TO EIA-418.
2. CONTROLLING DIMENSION: MILLIMETER.
3. DIMENSION MEASURED @ HUB.
4. INCLUDES FLANGE DISTORTION @ OUTER EDGE.

Notes:

① Repetitive rating; pulse width limited by max. junction temperature.

② Starting $T_J = 25°C$, $L = 4.2mH$ $R_G = 25\Omega$, $I_{AS} = 11A$.

③ Pulse width ≤ 400µs; duty cycle ≤ 2%.

④ This is only applied to TO-220AB package

⑤ This is applied to D^2Pak, when mounted on 1" square PCB (FR-4 or G-10 Material).
For recommended footprint and soldering techniques refer to application note #AN-994.

⑥ $I_{SD} \leq 11A$, $di/dt \leq 344A/\mu s$, $V_{DD} \leq V_{(BR)DSS}$, $T_J \leq 175°C$

International
IOR Rectifier

IR WORLD HEADQUARTERS: 233 Kansas St., El Segundo, California 90245, USA Tel: (310) 252-7105
IR EUROPEAN REGIONAL CENTER: 439/445 Godstone Rd, Whyteleafe, Surrey CR3 OBL, UK Tel: ++ 44 (0)20 8645 8000
IR CANADA: 15 Lincoln Court, Brampton, Ontario L6T3Z2, Tel: (905) 453 2200
IR GERMANY: Saalburgstrasse 157, 61350 Bad Homburg Tel: ++ 49 (0) 6172 96590
IR ITALY: Via Liguria 49, 10071 Borgaro, Torino Tel: ++ 39 011 451 0111
IR JAPAN: K&H Bldg., 2F, 30-4 Nishi-Ikebukuro 3-Chome, Toshima-Ku, Tokyo 171 Tel: 81 (0)3 3983 0086
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Data and specifications subject to change without notice. 10/00

International
IOR Rectifier

PD- 92004

SMPS MOSFET

IRF740A

HEXFET® Power MOSFET

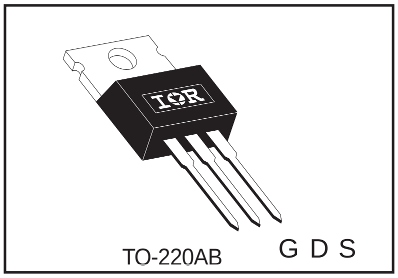
Applications

- Switch Mode Power Supply (SMPS)
- Uninterruptable Power Supply
- High speed power switching

V_{DSS}	Rds(on) max	I_D
400V	**0.55Ω**	**10A**

Benefits

- Low Gate Charge Qg results in Simple Drive Requirement
- Improved Gate, Avalanche and dynamic dv/dt Ruggedness
- Fully Characterized Capacitance and Avalanche Voltage and Current
- Effective Coss specified (See AN 1001)



Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	10	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	6.3	
I_{DM}	Pulsed Drain Current ①	40	
P_D @T_C = 25°C	Power Dissipation	125	W
	Linear Derating Factor	1.0	W/°C
V_{GS}	Gate-to-Source Voltage	± 30	V
dv/dt	Peak Diode Recovery dv/dt ③	5.9	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 150	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torqe, 6-32 or M3 screw	10 lbf•in (1.1N•m)	

Typical SMPS Topologies:

- Single transistor Flyback Xfmr. Reset
- Single Transistor Forward Xfmr. Reset
  (Both for US Line Input only)

Notes ① through ⑤ are on page 8

Static @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	400	—	—	V	V_{GS} = 0V, I_D = 250µA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—	0.48	—		V/°C Reference to 25°C, I_D = 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—	—	0.55	Ω	V_{GS} = 10V, I_D = 6.0A ④
$V_{GS(th)}$	Gate Threshold Voltage	2.0	—	4.0	V	V_{DS} = V_{GS}, I_D = 250µA
I_{DSS}	Drain-to-Source Leakage Current	—	—	25	µA	V_{DS} = 400V, V_{GS} = 0V
		—	—	250		V_{DS} = 320V, V_{GS} = 0V, T_J = 125°C
I_{GSS}	Gate-to-Source Forward Leakage	—	—	100	nA	V_{GS} = 30V
	Gate-to-Source Reverse Leakage	—	—	-100		V_{GS} = -30V

Dynamic @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
g_{fs}	Forward Transconductance	4.9	—	—	S	V_{DS} = 50V, I_D = 6.0A
Q_g	Total Gate Charge	—	—	36	nC	I_D = 10A
Q_{gs}	Gate-to-Source Charge	—	—	9.9		V_{DS} = 320V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	—	16		V_{GS} = 10V, See Fig. 6 and 13 ④
$t_{d(on)}$	Turn-On Delay Time	—	10	—	ns	V_{DD} = 200V
t_r	Rise Time	—	35	—		I_D = 10A
$t_{d(off)}$	Turn-Off Delay Time	—	24	—		R_G = 10Ω
t_f	Fall Time	—	22	—		R_D = 19.5Ω,See Fig. 10 ④
C_{iss}	Input Capacitance	—	1030	—	pF	V_{GS} = 0V
C_{oss}	Output Capacitance	—	170	—		V_{DS} = 25V
C_{rss}	Reverse Transfer Capacitance	—	7.7	—		ƒ = 1.0MHz, See Fig. 5
C_{oss}	Output Capacitance	—	1490	—		V_{GS} = 0V, V_{DS} = 1.0V, ƒ = 1.0MHz
C_{oss}	Output Capacitance	—	52	—		V_{GS} = 0V, V_{DS} = 320V, ƒ = 1.0MHz
C_{oss} eff.	Effective Output Capacitance	—	61	—		V_{GS} = 0V, V_{DS} = 0V to 320V ⑤

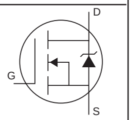
Avalanche Characteristics

	Parameter	Typ.	Max.	Units
E_{AS}	Single Pulse Avalanche Energy②	—	630	mJ
I_{AR}	Avalanche Current①	—	10	A
E_{AR}	Repetitive Avalanche Energy①	—	12.5	mJ

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	1.0	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient	—	62	

Diode Characteristics

	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—	—	10	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode) ①	—	—	40		
V_{SD}	Diode Forward Voltage	—	—	2.0	V	T_J = 25°C, I_S = 10A, V_{GS} = 0V ④
t_{rr}	Reverse Recovery Time	—	240	360	ns	T_J = 25°C, I_F = 10A
Q_{rr}	Reverse RecoveryCharge	—	1.9	2.9	µC	di/dt = 100A/µs ④
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by L_S+L_D)				

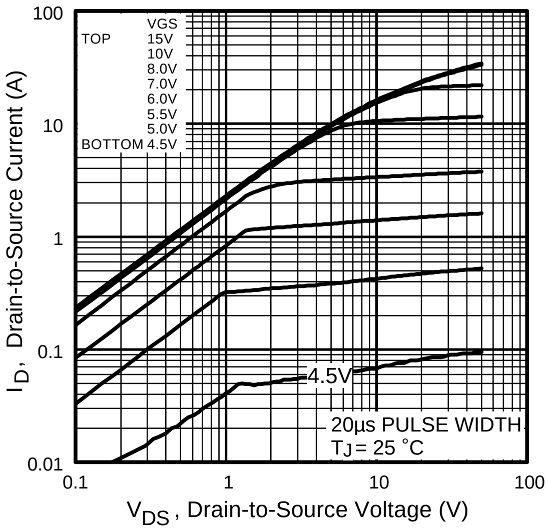


Fig 1. Typical Output Characteristics

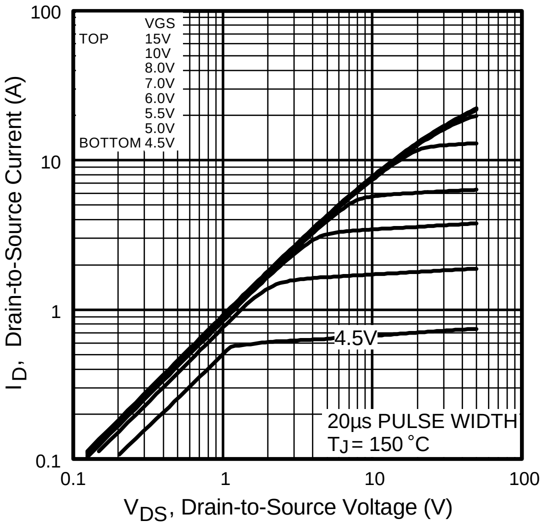


Fig 2. Typical Output Characteristics

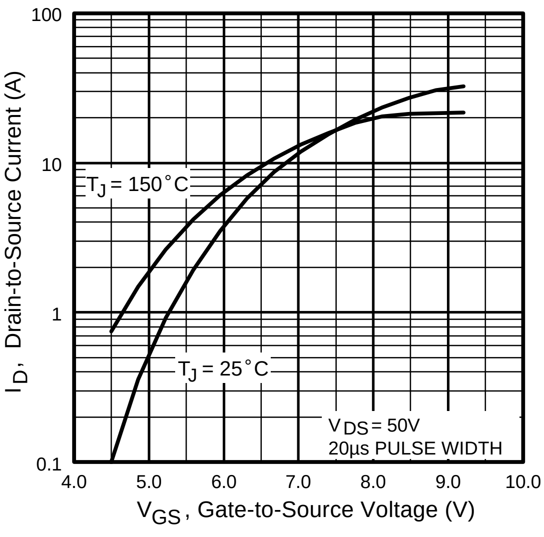


Fig 3. Typical Transfer Characteristics

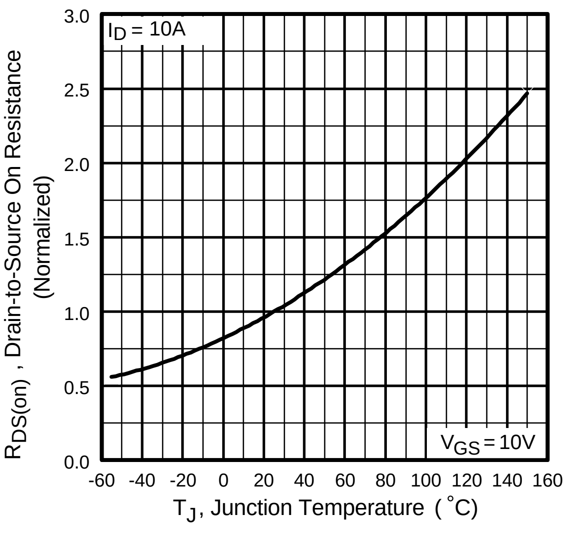


Fig 4. Normalized On-Resistance Vs. Temperature

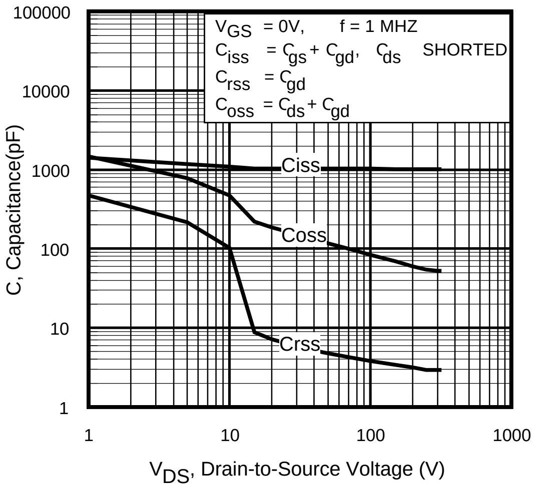


Fig 5. Typical Capacitance Vs. Drain-to-Source Voltage

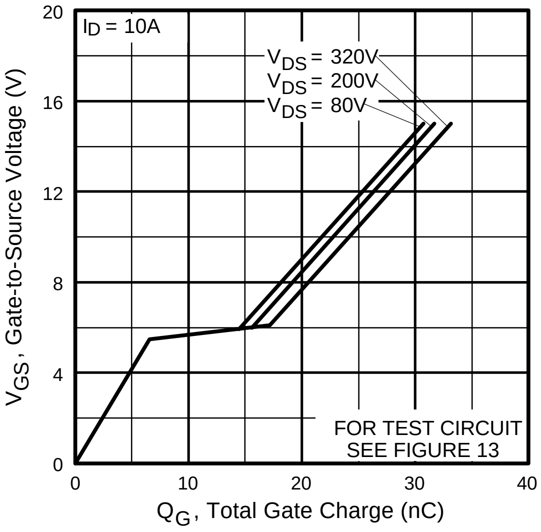


Fig 6. Typical Gate Charge Vs. Gate-to-Source Voltage

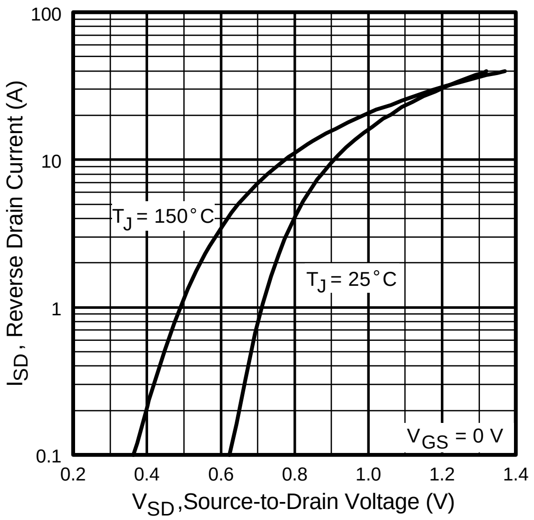


Fig 7. Typical Source-Drain Diode Forward Voltage

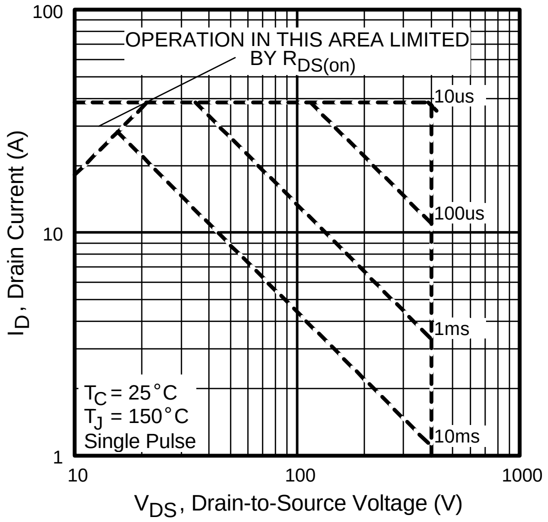


Fig 8. Maximum Safe Operating Area

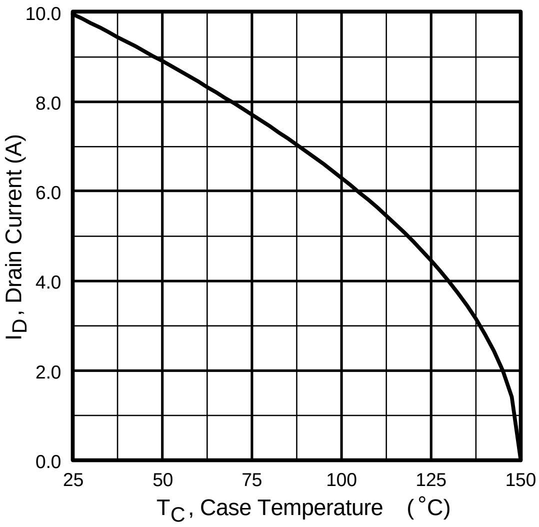


Fig 9. Maximum Drain Current Vs. Case Temperature

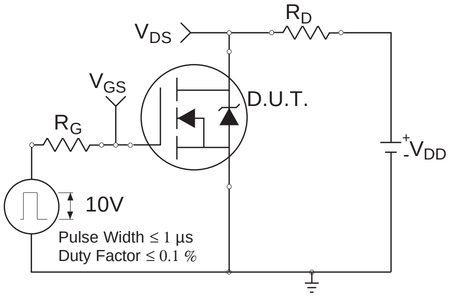


Fig 10a. Switching Time Test Circuit

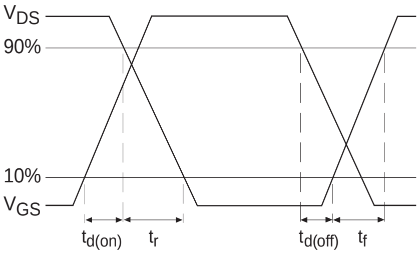


Fig 10b. Switching Time Waveforms

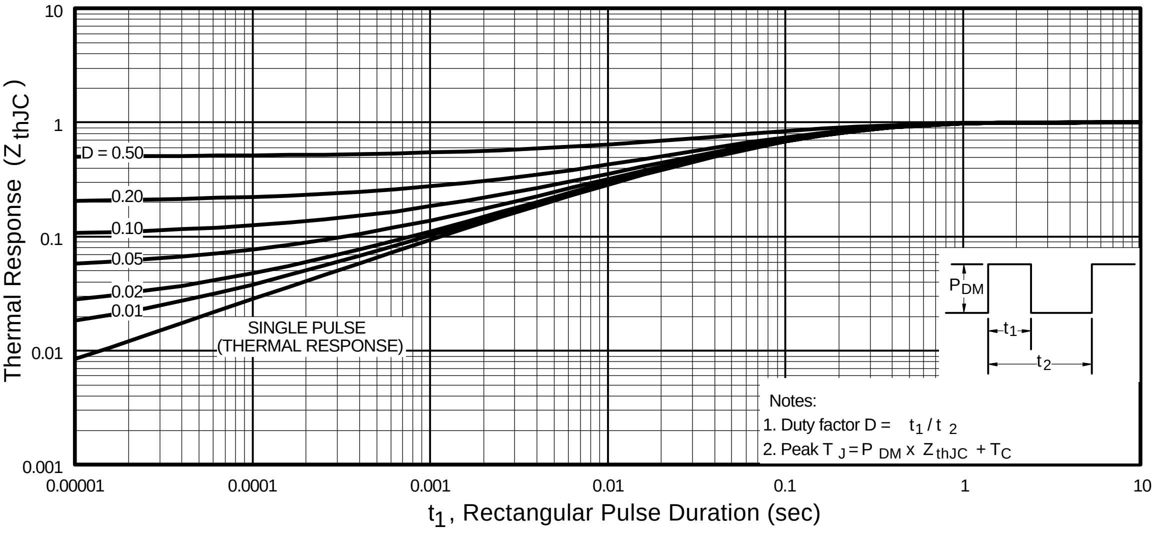


Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

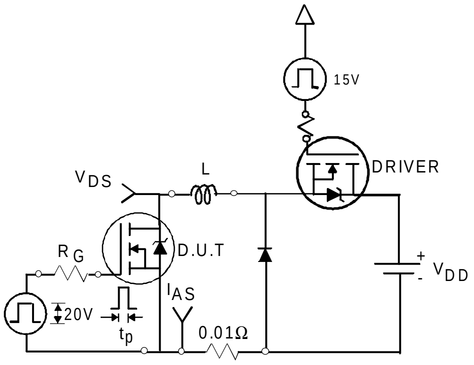


Fig 12a. Unclamped Inductive Test Circuit

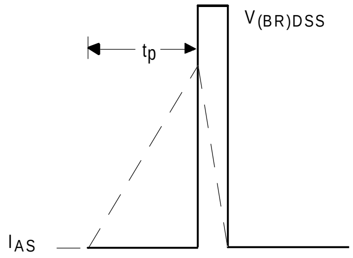


Fig 12b. Unclamped Inductive Waveforms

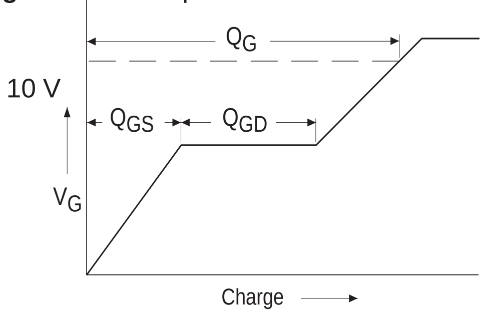


Fig 13a. Basic Gate Charge Waveform

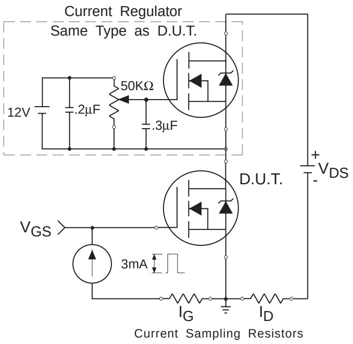


Fig 13b. Gate Charge Test Circuit

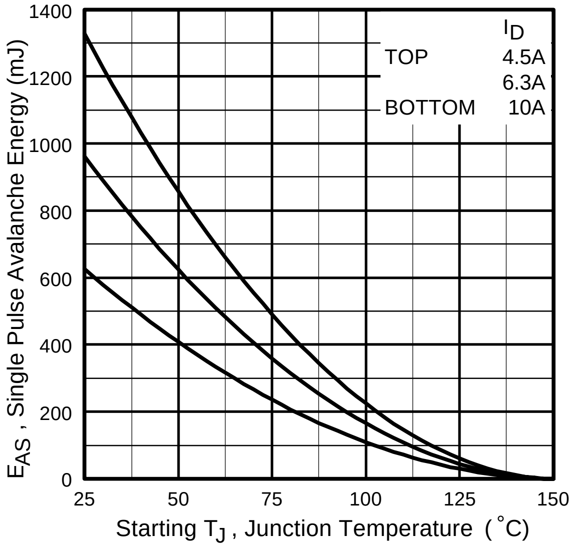


Fig 12c. Maximum Avalanche Energy Vs. Drain Current

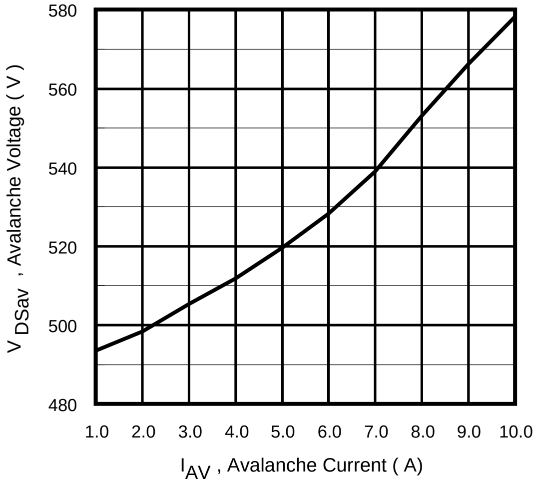
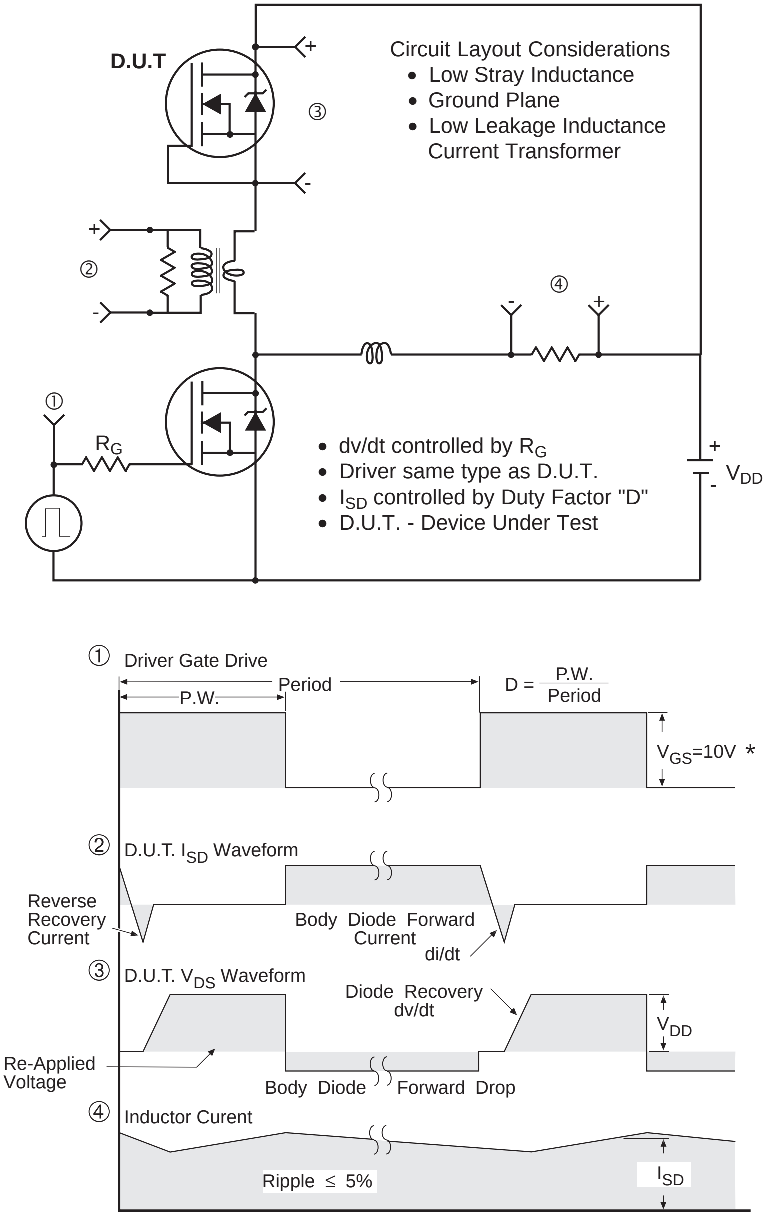


Fig 12d. Typical Drain-to-Source Voltage Vs. Avalanche Current

Peak Diode Recovery dv/dt Test Circuit



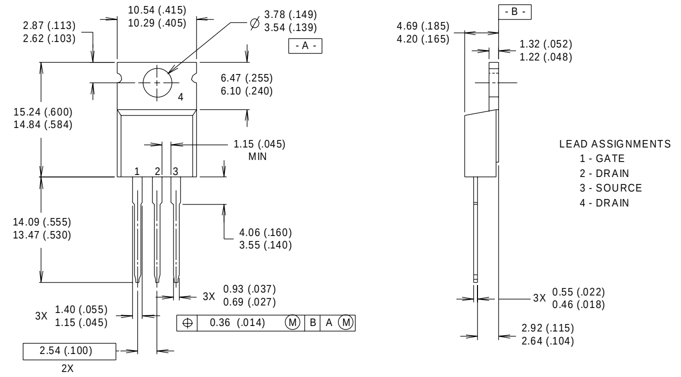
* V_{GS} = 5V for Logic Level Devices

Fig 14. For N-Channel HEXFETS

Package Outline

TO-220AB Outline

Dimensions are shown in millimeters (inches)



NOTES:

1 DIMENSIONING & TOLERANCING PER ANSI Y14.5M, 1982.

2 CONTROLLING DIMENSION : INCH

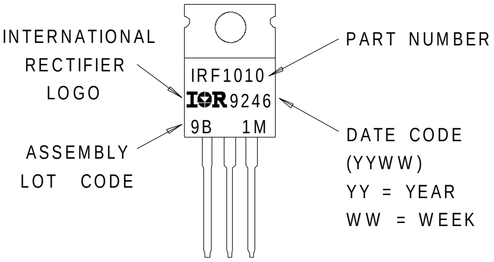
3 OUTLINE CONFORMS TO JEDEC OUTLINE TO-220AB.

4 HEATSINK & LEAD MEASUREMENTS DO NOT INCLUDE BURRS.

Part Marking Information

TO-220AB

EXAMPLE : THIS IS AN IRF1010
WITH ASSEMBLY
LOT CODE 9B1M



Notes:

① Repetitive rating; pulse width limited by max. junction temperature. (See fig. 11)

② Starting $T_J = 25°C$, $L = 12.6mH$ $R_G = 25\Omega$, $I_{AS} = 10A$. (See Figure 12)

③ $I_{SD} \le 10A$, $di/dt \le 330A/\mu s$, $V_{DD} \le V_{(BR)DSS}$, $T_J \le 150°C$

④ Pulse width ≤ 300µs; duty cycle ≤ 2%.

⑤ C_{oss} eff. is a fixed capacitance that gives the same charging time as C_{oss} while V_{DS} is rising from 0 to 80% V_{DSS}

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http://www.irf.com/ *Data and specifications subject to change without notice. 9/99*

Supertex inc. **HV214**

Initial Release

250V Low Charge Injection 8-Channel High Voltage Analog Switch

Features

- HVCMOS® technology for high performance
- Very low quiescent power dissipation – 10µA
- Low parasitic capacitances
- DC to 10MHz analog signal frequency
- -60dB typical output off isolation at 5MHz
- CMOS logic circuitry for low power
- Excellent noise immunity
- On-chip shift register, latch and clear logic circuitry
- Flexible high voltage supplies
- Surface mount package available

Applications

- Medical ultrasound imaging
- Piezoelectric transducer drivers
- Inkjet printer heads
- Optical MEMS modules

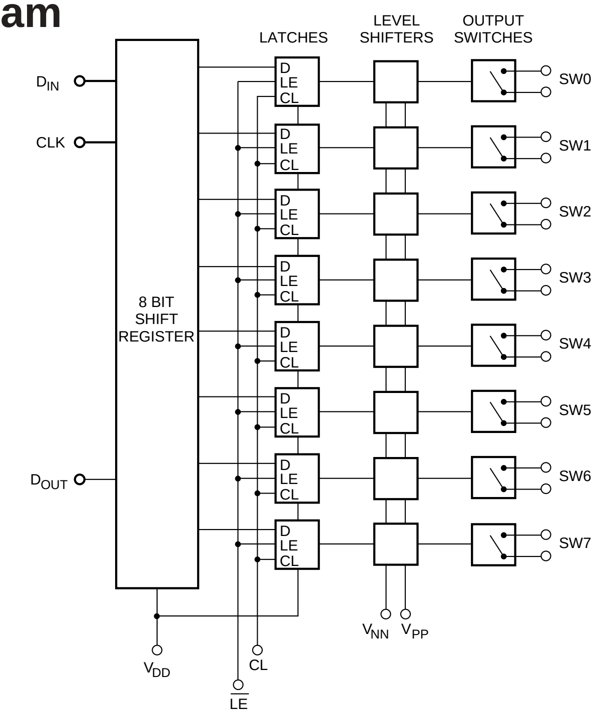
General Description

The Supertex HV214 is a low charge injection 8-channel high voltage analog switch integrated circuit (IC) intended for use in applications requiring high voltage switching controlled by low voltage control signals, such as medical ultrasound imaging, piezoelectric transducer drivers, inkjet printer heads and optical MEMS modules.

Input data is shifted into an 8-bit shift register that can then be retained in an 8-bit latch. To reduce any possible clock feedthrough noise, the latch enable bar should be left high until all bits are clocked in. Data are clocked in during the rising edge of the clock. Using HVCMOS® technology, this device combines high voltage bilateral DMOS switches and low power CMOS logic to provide efficient control of high voltage analog signals.

The device is suitable for various combinations of high voltage supplies, e.g., V_{PP}/V_{NN}: +40V/-210V, +125V/-125V, +210V/-40V.

Block Diagram



09/17/02

Ordering Information

$V_{PP} - V_{NN}$	Package Options		
	28-lead plastic chip carrier	**48-lead TQFP**	**Die**
250V	HV214PJ	HV214FG	HV214X

Electrical Characteristics

Symbol	Parameter	Min	Typ	Max	Units	Conditions	

DC Electrical Characteristics (T_A=25° C, over recommended operating conditions unless otherwise noted)

R_{ONS}	Small signal switch on-resistance			55	Ω	I_{SIG}=5.0mA	V_{PP} = +40V, V_{NN} = -210V
				49		I_{SIG}=200mA	
				42		I_{SIG}=5.0mA	V_{PP} = +125V, V_{NN} = -125V
				36		I_{SIG}=200mA	
				38		I_{SIG}=5.0mA	V_{PP} = +210V, V_{NN} = -40V
				32		I_{SIG}=200mA	
ΔR_{ONS}	Small signal switch on-resistance			20	%	I_{SIG} = 5mA, V_{PP} = +125V, V_{NN} = -125V	
R_{ONL}	Large signal switch on-resistance		23		Ω	V_{SIG} = V_{PP}-10V, I_{SIG} = 1A	
I_{SOL}	Switch off leakage per switch			10	µA	V_{SIG} = V_{PP}-10V and V_{NN}+10V	
	DC offset switch off			300	mV	R_{LOAD} = 100KΩ	
	DC offset switch on			500	mV	R_{LOAD} = 100KΩ	
I_{PPQ}	Quiescent V_{PP} supply current			50	µA	All switches off	
I_{NNQ}	Quiescent V_{NN} supply current			-50	µA	All switches off	
I_{PPQ}	Quiescent V_{PP} supply current			50	µA	All switches on, I_{SW} = 5mA	
I_{PPQ}	Quiescent V_{NN} supply current			-50	µA	All switches on, I_{SW} = 5mA	
	Switch output peak current			2.0	A	V_{SIG} duty cycle 0.1%	
f_{SW}	Output switch frequency			50	KHz	Duty cycle = 50%	
I_{PP}	Average V_{PP} supply current			7.0	mA	V_{PP}=+40V, V_{NN}=-210V	All output switches are turning On and Off at 50Khz with no load.
				5.0		V_{PP}=+125V, V_{NN}=-125V	
				5.0		V_{PP}=+210V, V_{NN}=-40V	
I_{NN}	Average V_{NN} supply current			-7.0		V_{PP}=+40V, V_{NN}=-210V	
				-5.0		V_{PP}=+125V, V_{NN}=-125V	
				-5.0		V_{PP}=+210V, V_{NN}=-40V	
I_{DDQ}	Quiescent V_{DD} supply current			10	µA		
I_{DD}	Average VDD supply Current			4.0	mA	f_{CLK} = 5MHz, V_{DD} = 5.0V	
I_{SOR}	Data out source current	0.45			mA	V_{OUT} = V_{DD}-0.7V	
I_{SINK}	Data out sink current	0.45			mA	V_{OUT} = 0.7V	
C_{IN}	Logic input capacitance			10	pF		
T_A	Ambient temperature range	0		70	° C		

Electrical Characteristics

AC Electrical Characteristics (V_{DD}=5V, T_A=25° C, over recommended operating conditions unless otherwise noted)

Symbol	Parameter	Min	Typ	Max	Units	Conditions
t_{SD}	Set up time before LE* Rises	150			ns	
t_{WLE}	Time width of LE*	150			ns	
t_{DO}	Clock delay time to data out			150	ns	
t_{WCL}	Time width of CL	150			ns	
t_{SU}	Set up time data to clock	15	8.0		ns	
t_H	Hold time data from Clock	35			ns	
f_{CLK}	Clock frequency			5.0	MHz	50% duty cycle, $f_{DATA} = f_{CLK}/2$
t_R, t_F	Clock rise and fall times			50	ns	
T_{ON}	Turn on time			5.0	µs	$V_{SIG} = V_{PP}$-10V, R_{LOAD} =10kΩ
T_{OFF}	Turn off time			5.0	µs	$V_{SIG} = V_{PP}$-10V, R_{LOAD} =10kΩ
dv/dt	Maximum V_{SIG} slew rate			20	V/ns	V_{PP} = +40V, V_{NN} = -210V
				20		V_{PP} = +125V, V_{NN} = -125V
				20		V_{PP} = +210V, V_{NN} = -40V
KO	Off isolation	-30			dB	f = 5.0MHz, 1KΩ/15pF load
		-58				f = 5.0MHz, 50Ω load
K_{CR}	Switch crosstalk	-60			dB	f = 5.0MHz, 50Ω load
I_{ID}	Output switch isolation diode current			300	mA	300ns pulse width, 2.0% duty cycle
$C_{SG(OFF)}$	Off capacitance SW to Gnd	5.0	12	17	pF	0V, f = 1MHz
$C_{SG(ON)}$	On capacitance SW to Gnd	25	38	50	pF	0V, f = 1MHz
$+V_{SPK}$	Output Voltage Spike			200	mV	V_{PP} = +40V, V_{NN} = -210V, R_{LOAD} = 50Ω
$-V_{SPK}$				200		
$+V_{SPK}$				200	mV	V_{PP} = +125V, V_{NN} = -125V, R_{LOAD} = 50Ω
$-V_{SPK}$				200		
$+V_{SPK}$				200	mV	V_{PP} = +210V, V_{NN} = -40V, R_{LOAD} = 50Ω
$-V_{SPK}$				200		

Absolute Maximum Ratings*

V_{DD} Logic power supply voltage		-0.5V to +15V
V_{PP} - V_{NN} Supply voltage		260V
V_{PP} Positive high voltage supply		-0.5V to V_{NN} +250V
V_{NN} Negative high voltage supply		+0.5V to -260V
Logic input voltages		-0.5V to V_{DD} +0.3V
Analog Signal Range		V_{NN} to V_{PP}
Peak analog signal current/channel		2.5A
Storage temperature		-65°C to +150°C
Power dissipation	28-pin PLCC	1.2W
	48 lead TQFP	1.0W

* Absolute Maximum Ratings are those values beyond which damage to the device may occur. Functional operation under these conditions is not implied. Continuous operation of the device at the absolute rating level may affect device reliability.

Operating Conditions

Symbol	Parameter	Value
V_{DD}	Logic power supply voltage	4.5V to 13.2V
V_{PP}	Positive high voltage supply	40V to V_{NN}+ 250V
V_{NN}	Negative high voltage supply	-40V to -210V
V_{IH}	High-level input voltage	V_{DD} -1.5V to V_{DD}
V_{IL}	Low-level input voltage	0V to 1.5V
V_{SIG}	Analog signal voltage peak to peak	V_{NN} +10V to V_{PP} -10V
T_A	Operating free air-temperature	0°C to 70°C

Power Up/Down Sequence:

1 Power up/down sequence is arbitrary except GND must be powered-up first and powered-down last.
2 V_{SIG} must be $V_{NN} \leq V_{SIG} \leq V_{PP}$ or floating during power up/down transistion.
3 Rise and fall times of power supplies V_{DD}, V_{PP}, and V_{NN} should not be less than 1.0msec.

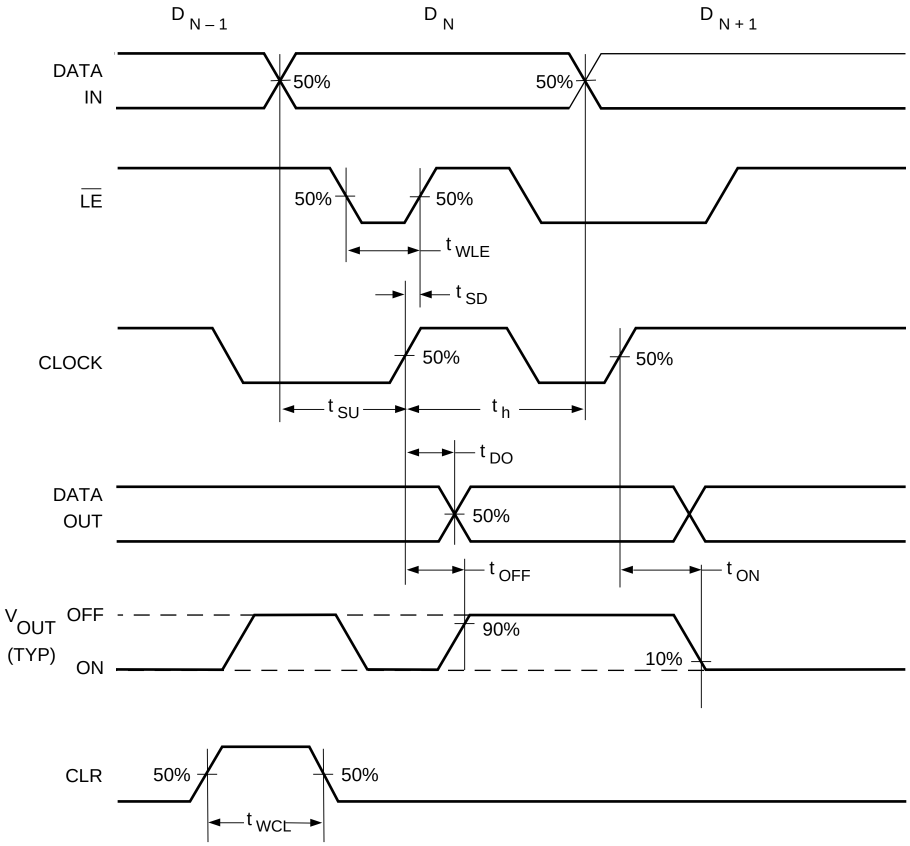
Truth Table

D0	D1	D2	D3	D4	D5	D6	D7	$\overline{LE}$	CL	SW0	SW1	SW2	SW3	SW4	SW5	SW6	SW7
L								L	L	OFF							
H								L	L	ON							
	L							L	L		OFF						
	H							L	L		ON						
		L						L	L			OFF					
		H						L	L			ON					
			L					L	L				OFF				
			H					L	L				ON				
				L				L	L					OFF			
				H				L	L					ON			
					L			L	L						OFF		
					H			L	L						ON		
						L		L	L							OFF	
						H		L	L							ON	
							L	L	L								OFF
							H	L	L								ON
X	X	X	X	X	X	X	X	H	L	HOLD PREVIOUS STATE							
X	X	X	X	X	X	X	X	X	H	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

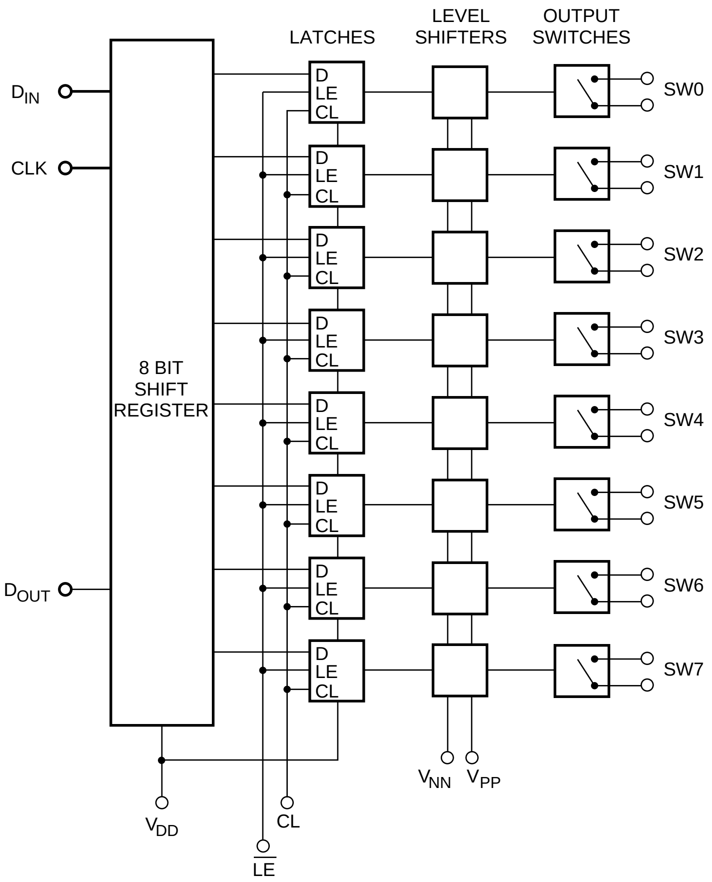
Notes:

1. The eight switches operate independently.
2. Serial data is clocked in on the L→ H transition CLK.
3. The switches go to a state retaining their present condition at the rising edge of $\overline{LE}$. When $\overline{LE}$ is low the shift register data flows through the latch.
4. D_{OUT} is high when switch 7 is on.
5. Shift register clocking has no effect on the switch states if $\overline{LE}$ is H.
6. The clear input overrides all other inputs.

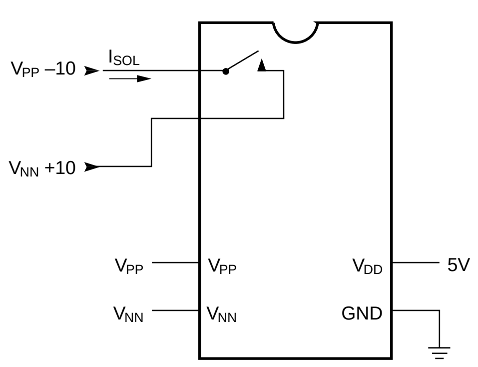
Logic Timing Waveforms



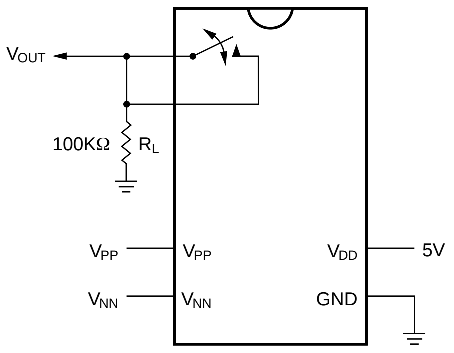
Block Diagram



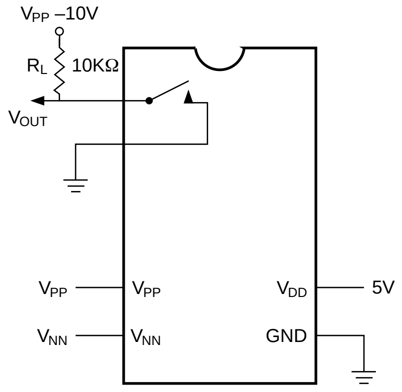
Test Circuits



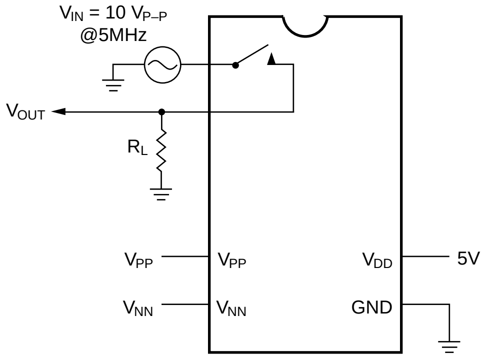
Switch OFF Leakage



DC Offset ON/OFF

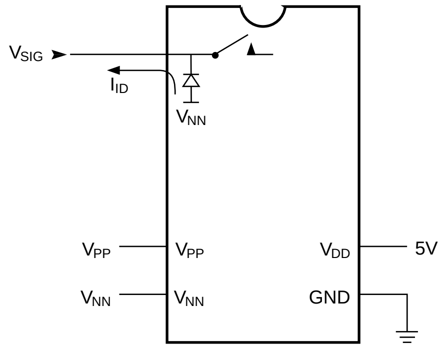


T_{ON}/T_{OFF} Test Circuit

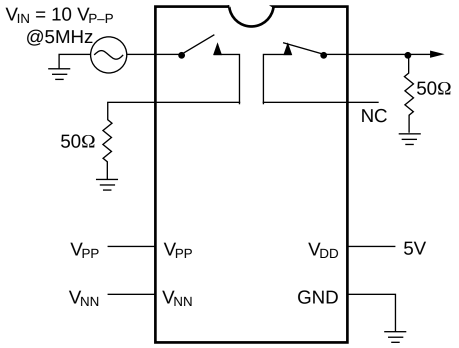


$K_O = 20\text{Log}\,\frac{V_{OUT}}{V_{IN}}$

OFF Isolation

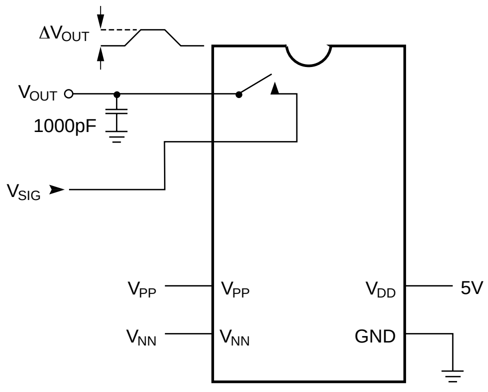


Isolation Diode Current



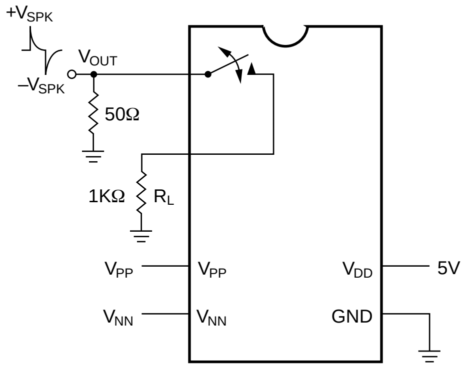
$K_{CR} = 20\text{Log}\,\frac{V_{OUT}}{V_{IN}}$

Crosstalk



$Q = 1000\text{pF} \times \Delta V_{OUT}$

Charge Injection



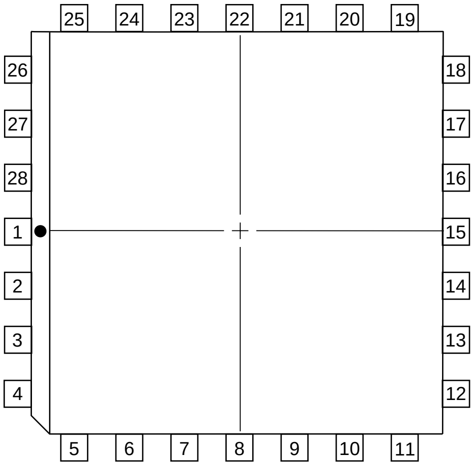
Output Voltage Spike

Pin Configurations

HV214 28 Pin J-Lead

Pin	Function	Pin	Function
1	SW3	15	N/C
2	SW3	16	D_{IN}
3	SW2	17	CLK
4	SW2	18	$\overline{LE}$
5	SW1	19	CL
6	SW1	20	D_{OUT}
7	SW0	21	SW7
8	SW0	22	SW7
9	N/C	23	SW6
10	V_{PP}	24	SW6
11	N/C	25	SW5
12	V_{NN}	26	SW5
13	GND	27	SW4
14	V_{DD}	28	SW4

Package Outlines



top view

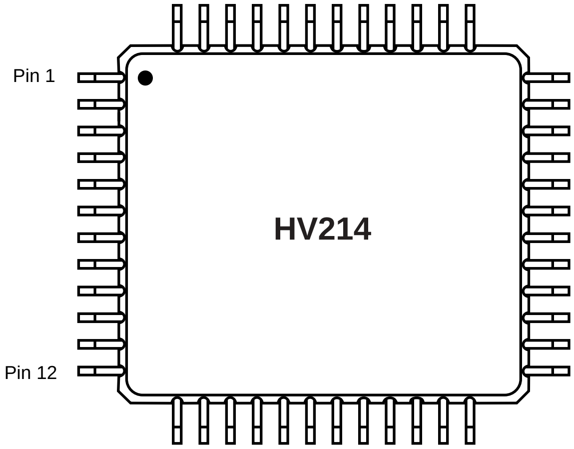
28-pin J-Lead Package

Pin Configurations

HV214 48-Pin TQFP

Pin	Function	Pin	Function
1	SW5	25	V_{NN}
2	N/C	26	N/C
3	SW4	27	N/C
4	N/C	28	GND
5	SW4	29	V_{DD}
6	N/C	30	N/C
7	N/C	31	N/C
8	SW3	32	N/C
9	N/C	33	D_{IN}
10	SW3	34	CLK
11	N/C	35	$\overline{LE}$
12	SW2	36	CLR
13	N/C	37	D_{OUT}
14	SW2	38	N/C
15	N/C	39	SW7
16	SW1	40	N/C
17	N/C	41	SW7
18	SW1	42	N/C
19	N/C	43	SW6
20	SW0	44	N/C
21	N/C	45	SW6
22	SW0	46	N/C
23	N/C	47	SW5
24	V_{PP}	48	N/C

Package Outlines



top view

48-pin TQFP

CRYDOM

Control over power

Series CMX

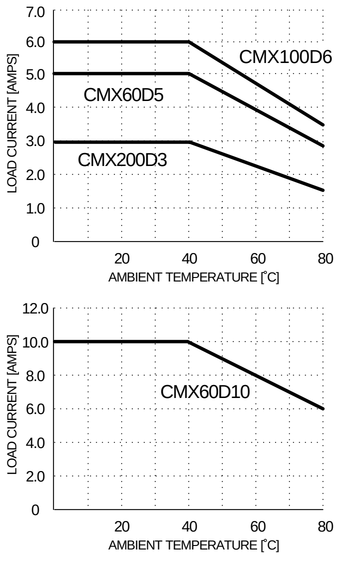
3-10 Amp • 0-60, 0-100 Vdc, 0-200Vdc • DC Output SIP

- **MOSFET Output**
- **Extra Low On-State Resistance**

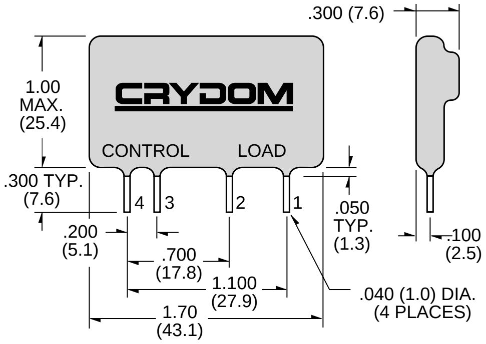
DC output SPST-NO solid state relays use MOSFET output for high switching capabilities in a PC-mount air-cooled package. Pinouts are compatible with Series 6 and ODC type I/O modules.

Manufactured in Crydom's ISO 9001 Certified facility for optimum product performance and reliability.

CURRENT DERATING CURVES



Max. Load Current vs. Temp.



PIN 1: +DC LOAD
PIN 2: –DC LOAD
PIN 3: +DC CONTROL
PIN 4: –DC CONTROL

All dimensions are in inches (millimeters)

APPROVALS

UL E116950 (6A & 10A Models)

MODEL NO.	**CMX60D5**	**CMX60D10**	**CMX100D6**	**CMX200D3**
INPUT SPECIFICATIONS ①				
Control Voltage Range	3.0-10.0 Vdc	3.0-10.0 Vdc	3.0-10.0 Vdc	4.0-10.0 Vdc
Nominal Input Impedance	300 Ohm	300 Ohm	300 Ohm	300 Ohm
Typical Input Current @ 5 Vdc	15 mAdc	15 mAdc	15 mAdc	15 mAdc
Must Turn On Voltage	3.0 Vdc	3.0 Vdc	3.0 Vdc	4.0 Vdc
Must Turn Off Voltage	1.0 Vdc	1.0 Vdc	1.0 Vdc	1.0 Vdc
OUTPUT SPECIFICATIONS ①③				
Operating Voltage Range	0-60 Vdc	0-60 Vdc	0-100 Vdc	0-200 Vdc
Load Current Range	0-5 Adc	0-10 Adc	0-6 Adc	0-3 Adc
Max. Surge Current, (10 msec)	60 Apk	100 Apk	100 Apk	30 Apk
Max.Off-State Leakage @ Rated Voltage	100 µAdc	100 µAdc ④	100 µAdc	100 µAdc
Max. On-State Resistance @ Rated Current (R_{DS-ON})	.10 Ohm	.018 Ohm	.040 Ohm	.20 Ohm
Max. On-State Voltage Drop @ Rated Current	0.5V	0.18V	0.24V	0.6 V
Max.Turn-On Time @ 10Vdc Control	1.0 msec	1.0 msec	1.0 msec	1.0 msec
Max. Turn-Off TIme @ 10Vdc Control	300 µsec	300 µsec	300 µsec	300 µsec

GENERAL SPECIFICATIONS

Dielectric Strength ②	2500 Vrms
Insulation Resistance (Min.) @ 500 Vdc ②	10^9 Ohm
Max. Capacitance (Input/Output)	15 pF
Ambient Operating Temperature Range	-30 to 80˚C
Ambient Storage Temperature Range	-30 to 125˚C

MECHANICAL SPECIFICATIONS

Weight: (typical)	0.4 oz. (11 g)
Encapsulation:	Thermally Conductive Epoxy

GENERAL NOTES

① All parameters at 25ºC unless otherwise specified.
② Dielectric and insulation resistance are measured between input and output.
③ Inductive loads should be diode suppressed.
④ At 55 Vdc.

For recommended applications and more information contact:
USA: Sales Support (877) 502-5500 **Tech Support** (877) 702-7700 **FAX** (619) 710-8540
Crydom Corp, 2320 Paseo de las Americas, Ste. 201, San Diego, CA 92154
Email: sales@crydom.com **WEB SITE:** http://www.crydom.com
UK: +44 (0)1202 365070 **FAX** +44 (0)1202 365090 Crydom International Ltd., 7 Cobham Road, Ferndown Industrial Estate, Ferndown, Dorset BH21 7PE, **Email**: intsales@crydom.com.
GERMANY: +49 (0)180 3000 506

ISO 9001 CERTIFIED

International
IOR Rectifier
HEXFET® Power MOSFET Photovoltaic Relay

PD 6.040D

Series PVT412

Microelectronic
Power IC Relay

Single Pole, Normally Open, 0-400V, 140mA AC/DC

General Description

The PVT412 Series Photovoltaic Relay is a single-pole, normally open solid-state relay that can replace electromechanical relays in many applications. It utilizes International Rectifier's proprietary HEXFET power MOSFET as the output switch, driven by an integrated circuit photovoltaic generator of novel construction. The output switch is controlled by radiation from a GaAlAs light emitting diode (LED) which is optically isolated from the photovoltaic generator.

These SSRs are specifically designed for worldwide telecom applications. PVT412L employs an active current-limiting circuitry enabling it to pass FCC Part 68 and other regulatory agency current surge requirements when overvoltage protection is provided. PVT412 does not employ the current-limiting circuitry and offers lower on-state resistance.

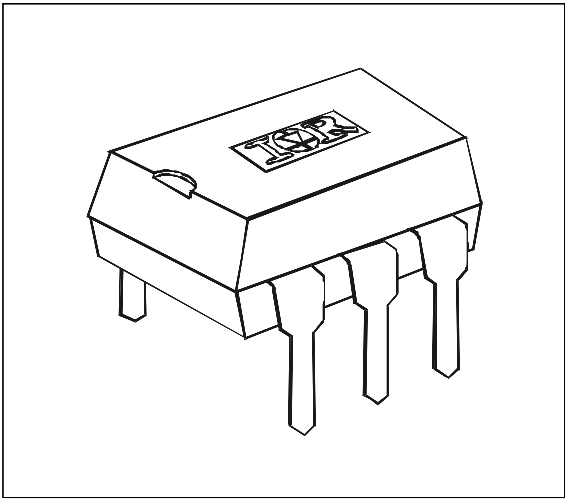
Series PVT412 Relays are packaged in a 6-lead molded DIP package with either through-hole or surface mount ('gull-wing') terminals. It is available in standard plastic shipping tubes or on tape-and-reel. Please refer to part identification information opposite.

Applications

- On/Off Hook switch
- Dial-Out relay
- Ring relay
- General switching

PVT412L Features

- HEXFET Power MOSFET output
- Bounce-free operation
- 4,000 VRMS I/O isolation
- Load current limiting
- Linear AC/DC operation
- Solid-State reliability
- UL recognized and CSA certified



Part Identification

PVT412L	current limit, through-hole
PVT412LS	current limit, surface-mount
PVT412LS-T	current limit, surface-mount, Tape and Reel
PVT412	no current limit, through-hole
PVT412S	no current limit, surface-mount
PVT412S-T	no current limit, surface-mount, Tape and Reel

(HEXFET is the registered trademark for International Rectifier Power MOSFETs)

Electrical Specifications (-40°C ≤ T_A ≤ +85°C unless otherwise specified)

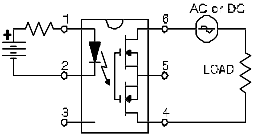
INPUT CHARACTERISTICS	Part Numbers		Units
	PVT412L	PVT412	
Minimum Control Current (see figures 1 and 2)	3.0		mA
Maximum Control Current for Off-State Resistance	0.4		mA
Control Current Range (Caution: current limit input LED, see figure 6)	3.0 to 25		mA
Maximum Reverse Voltage	7.0		V

OUTPUT CHARACTERISTICS	PVT412L		PVT412	
Operating Voltage Range	0 to ±400			$V_{\text{(DC or AC peak)}}$
Maximum Load Current @ T_A=+40°C 5mA Control (see figures1 and 2)				
A Connection	120		140	mA (AC or DC)
B Connection	130		150	mA (DC)
C Connection	200		210	mA (DC)
Maximum On-State Resistance @T_A=+25°C For 50mA Pulsed Load, 5mA Control (see figure 4)				
A Connection	35		27	Ω
B Connection	18		14	Ω
C Connection	9		7	Ω
Maximum Off-State Leakage @T_A=+25°C, ±400V (see figure 5)	1.0			µA
Current Limit @T_A=+25°C, For 5mA Control Current:				
Connection:	**A**	**C**		
Minimum	130	260	n/a	mA
Maximum	220	440	n/a	mA
Complies with FCC Part 68 Surge Requirements*	yes		yes	
Maximum Turn-On Time @T_A=+25°C (see figure 7) For 50mA, 100 V_{DC} load, 5mA Control	2.0			ms
Maximum Turn-Off Time @T_A=+25°C (see figure 7) For 50mA, 100 V_{DC} load, 5mA Control	0.5			ms
Maximum Thermal Offset Voltage @ 5mA Control	0.5			µV
Maximum Output Capacitance @ 50V_{DC}	12			pF

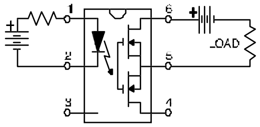
GENERAL CHARACTERISTICS		ALL MODELS	
Minimum Dielectric Strength, Input-Output		4000	V_{RMS}
Minimum Insulation Resistance, Input-Output @T_A=+25°C, 50%RH, 100V_{DC}		10^{12}	Ω
Maximum Capacitance, Input-Output		1.0	pF
Maximum Pin Soldering Temperature (10 seconds maximum)		+260	°C
Ambient Temperature Range:	Operating	-40 to +85	
	Storage	-40 to +100	

Connection Diagrams

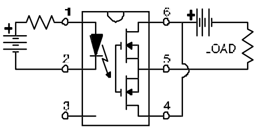
"A" Connection



"B" Connection



"C" Connection



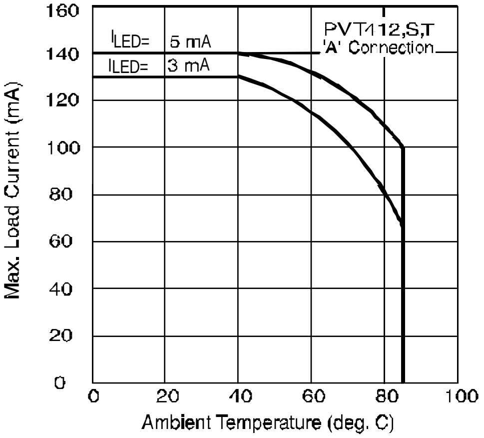


Figure 1. Current Derating Curves*

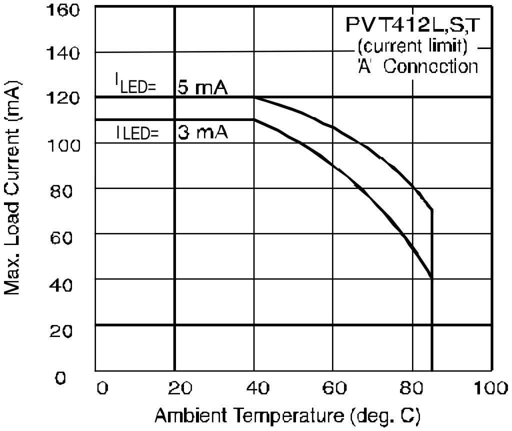


Figure 2. Current Derating Curves*

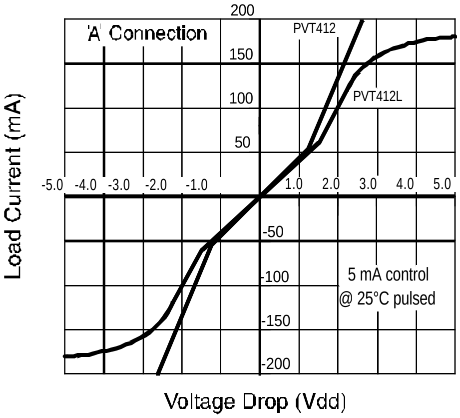


Figure 3. Linearity Characteristics

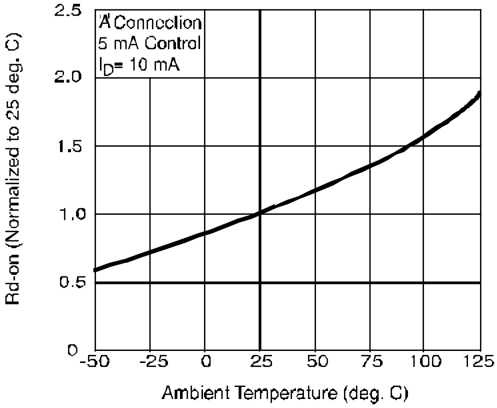


Figure 4. Typical Normalized On-Resistance

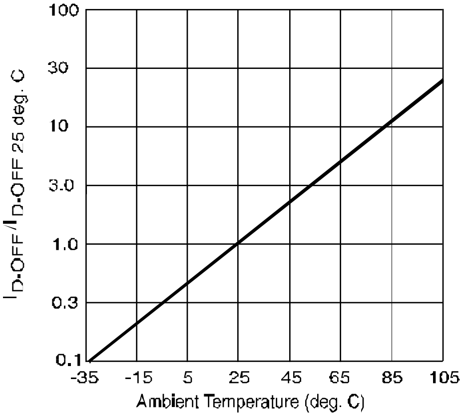


Figure 5. Typical Normalized Off-State Leakage

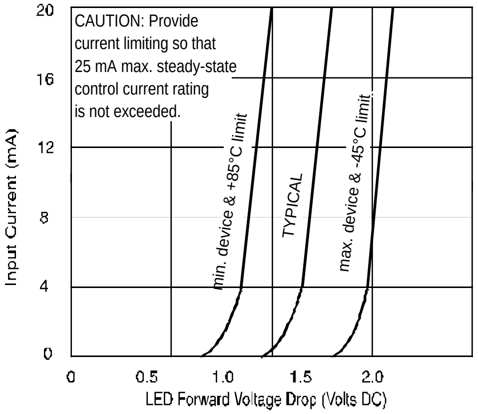


Figure 6. Input Characteristics (Current Controlled)

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* Derating of 'B' and 'C' connection at +85°C will be 70% of that specified at +40°C and is linear from +40°C to +85°C.

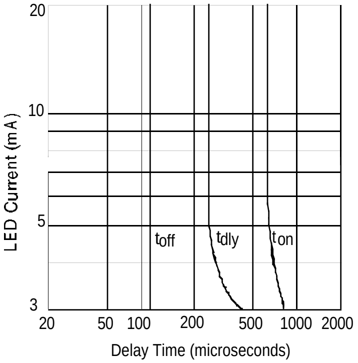


Figure 7. Typical Delay Times

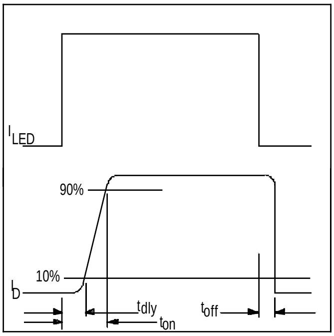


Figure 8. Delay Time Definitions

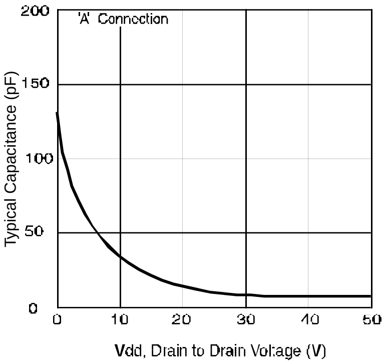


Figure 9. Typical Output Capacitance

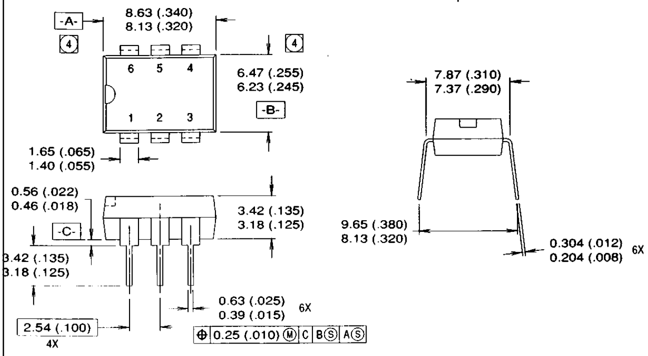
Case Outline

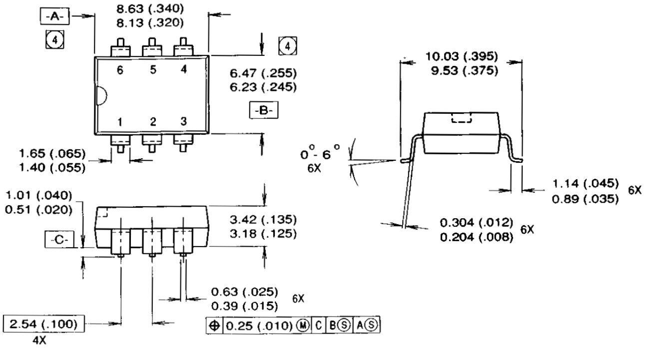
Dimensions in millimeters (inches)

Mechanical Specifications:

1. Dimensioning and tolerancing per ANSI Y14.5M-1982
2. Controlling Dimension: Inch

4 Dimension does not include mold protrusions. Mold protrusions shall not exceed 0.25 (.010).





Note: PVT412L relays will pass FCC Part 68 surge current requirements operating into rated load or short circuit when protected from overvoltage by a transient protection device such as a 175 VRMS rated MOV placed between the tip and ring terminals of the telephone line or across the output of the relay. PVT412 relays will pass the above FCC Part 68 requirements when overcurrent protection devices (such as fusible resistors) are placed in series with tip and ring lines in addition to the aforementioned overvoltage protection. Consult factory for additional information.

International Rectifier

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EUROPEAN HEADQUARTERS: Hurst Green, Oxted, Surrey RH8 9BB, UK Tel: ++ 44 1883 713215
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