MOTOROLA SEMICONDUCTOR

CIRCUITS MANUAL

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* New Products
* Design Limitations
* Power Control
* Inverters
* Regulators
* Ignition
* RF Transmitters

FOREWORD

This manual discusses some of the many practical circuits using power semiconductors. The circuits are intended to illustrate design principles and limitations of solid state devices. A broad frequency spectrum is covered -- dc to 240 Mc. The devices include p-n junctions such as low current rectifiers, zener diodes and the new high current multicell rectifiers; p-n-p devices including large junction germanium power transistors suitable for motor control as well as the latest silicon-epitaxial-annular-passivated RF amplifiers; PNPN silicon controlled rectifiers and gate controlled switches such as the steel can low-cost SCR; and completing the circle back to a p-n junction -- the varactor diode.

The object of this manual is to provide device and circuit information which is supplemental to data sheets, application notes, handbooks and other existing technical knowledge. We sincerely hope you find this reference manual a useful guide to practical circuitry.

The information and circuit diagrams in this manual have been carefully checked and are believed to be entirely reliable but no responsibility is assumed for inaccuracies. Moreover, complete information is not necessarily given for construction purposes. Neither the disclosure of any information contained herein nor the sale of semiconductor devices conveys any license under the patent rights of Motorola, Inc. or others.

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CONTENTS

The MCR1304 Controlled Rectifier

INTRODUCTION

The Motorola MCR1304 series of controlled rectifiers are suitable for applications requiring blocking voltages through 400 volts and RMS currents up to 8 amperes. These devices are packaged in a space-saving, economical steel can which provides considerable versatility of mounting. These devices are also available with modified packages, i. e., MCR1305 series with a mounting stud, MCR1604 series which is a single-ended three-lead case and the MCR1605 series which is a double-ended three-lead case.

As with any semiconductor device, these silicon controlled rectifiers must be operated within specified ratings for optimum and reliable performance. Semiconductor construction techniques require the use of solder as a bonding material in the controlled rectifier. To prevent damage to the processed silicon controlled rectifier die, hard solder with a sufficiently low melting point is used. Thus, in any processing of the completed controlled rectifier, the temperature must be kept below a predetermined value to prevent the solder from melting.

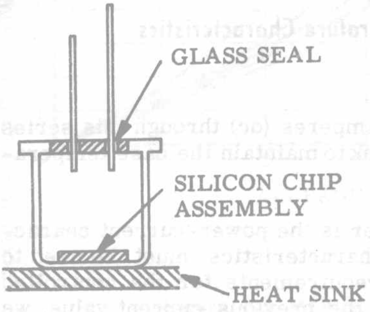

Figure 1-1 Placement of Silicon Die in Controlled Rectifier Can

As shown in Figure 1-1, the silicon controlled rectifier die is mounted directly to the bottom of the case which provides the shortest thermal path from the die to a heat sink. Obviously, the most effective method to heat sink these devices is to mount the bottom directly to the heat sink.

CONDUCTING CHARACTERISTICS

To keep within specified characteristics, the MCR1304 controlled rectifier junction, during operation, should not be allowed to exceed 100°C. The electrical limitation on this unit is 8 amperes (RMS). Imposing these two limiting values and the inherent values of thermal resistance and conducting voltage drop, the current-temperature characteristics can be determined, (Figure 1-2). Applying these characteristics to any operating condition is basically easy. For an operating current, (below the allowable maximum, determined by both magnitude and conduction angle) the temperature measured on the case of the controlled rectifier must be below the value determined from the current-temperature characteristics. Usually, either the dc condition at 180°C conduction angle state will be the worst-case operating condition because the average current drops more rapidly than the device limits with decreasing conduction angles.

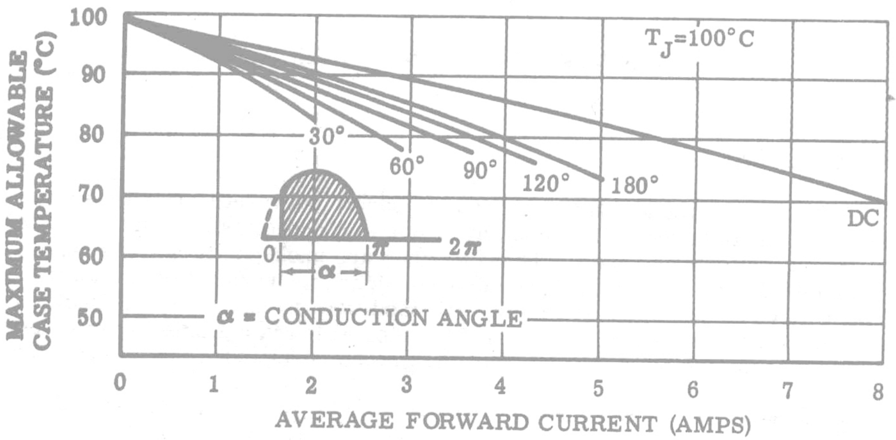

Figure 1-2 MCR1304 Current-Temperature Characteristics

For example, if it is desired to conduct 3 amperes (dc) through this series of controlled rectifiers, an adequate heat sink to maintain the case temperature below 90°C must be provided.

Also of interest to the design engineer is the power-current characteristics shown in Figure 1-3. These characteristics must be used to determine, analytically, the heat sinking requirements for the controlled rectifier circuit. From Figure 1-3, using the previous current value, we determine that the heat produced by 3.7 watts must be removed from the MCR1304 to insure proper operation. Experimentally, the design must be tested to insure proper operation, i.e. the case temperature should remain below that determined from Figure 1-2, (90°C in the example).

HEAT SINKING REQUIREMENTS

The versatility of the MCR1304 steel-can package allows it to be mounted in a wide variety of ways to meet individual requirements. Depending upon the thermal resistance value between the SCR case and a heat sink, any mounting method which satisfies the current derating curves may be used. Possible mounting media include: solder, epoxy cements; clips (fuse, resistor, transistor, special); clamps; commercial or special dissipators, retainers, coolers, and radiators.

A figure of merit which may be easily applied to any heat sinking arrangement is thermal resistance which is defined as the resistance to heat flow from a point at one temperature (T_1) to a point at a different temperature (T_2). The heat is produced by the power dissipated in the semiconductor (power = BTU/min). Mathematically, thermal Resistance = (T2-T1)/Power. The lower the thermal resistance the easier it will be to conduct the heat away, and the better will be the heat sink.

As previously discussed, the heat sinking requirements must be determined from the power-temperature characteristics of the controlled rectifier. Combining the MCR1304 characteristics and the definition of thermal resistance, we can determine heat sink requirement data, (Figure 1-4), in terms of heat sink thermal resistance.

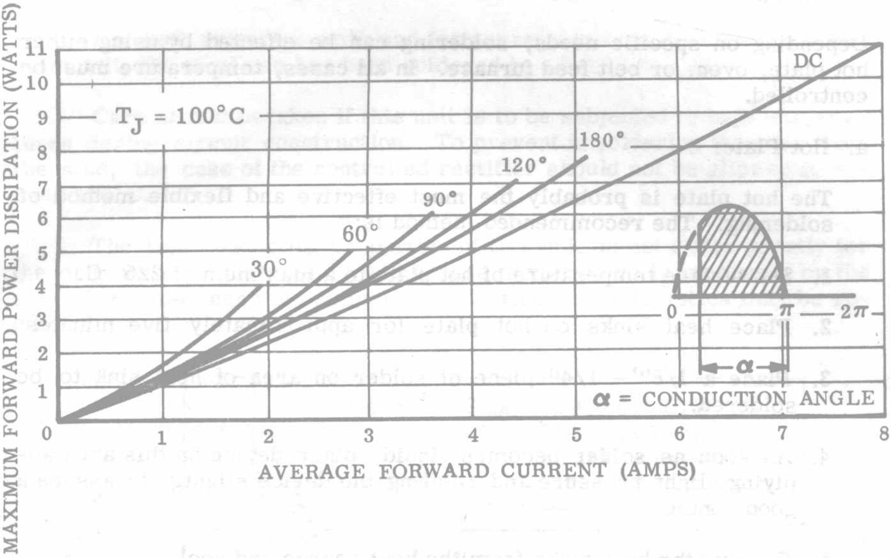

Figure 1-3 MCR1304 Power-Current Characteristics

SOLDERING THE MCR1304

One of the easiest and most efficient methods of heat sinking this controlled rectifier is to solder it directly to the heat sink. The following outline has been prepared as a step-by-step guide to soldering:

1. Materials Required:

   a. Solder:

   To prevent damage to the device, a relatively low temperature solder with a melting point between 175°C and 225°C must be used. The common lead-tin alloys are recommended since they are inexpensive, readily available, and they have a wide range of melting points in the temperature range required. Any lead-tin solder of less than 70 per cent lead content may be used. The 60/40 lead-tin alloy (melting point of 188°C) is the most practical in that it is generally a common stock item.

b. Flux:

Depending on the soldering method used, a flux may or may not be used. However, when used, a non-corrosive resin flux is recommended.

2. Soldering Methods:

Depending on specific needs, soldering can be effected by using either hot plate, oven, or belt feed furnace. In all cases, temperature must be controlled.

a. Hot Plate:

The hot plate is probably the most effective and flexible method of soldering. The recommended method is:

1. Set surface temperature of hot plate to a maximum of 225° C.

2. Place heat sinks on hot plate for approximately five minutes.

3. Place a 1/8" - 1/4" piece of solder on area of heat sink to be soldered.

4. As soon as solder becomes liquid, place device on this area applying slight pressure and rotating the device slightly to assure a good contact.

5. Remove the heat sinks from the heat source and cool.

6. Flux may be used if required. However, suitable wetting is achieved mechanically when the device is rotated in liquid solder.

b. Oven:

For an inert atmosphere such as N_2, dry air, etc., a flux is recommended. If H_2N_2 is available and used, flux should not be required. Again, temperature must be controlled.

c. Belt Feed Furnace:

The same procedures apply here as in the oven with the exception that possibly jigging may be required to hold the device and the heat sink in the proper position.

3. Heat Sink Material:

a. Since copper and most of its alloys present no problem in soldering, they probably are the most favorable heat sink material.

b. Stainless steel is difficult to solder. However, by using a strong acid flux filled preform, satisfactory soldering can be achieved.

c. For materials which do not solder too easily, such as aluminum, applying a tin coat to the material will usually simplify soldering.

MCR1305 - THE STUD VERSION OF THE MCR1304

For both prototype work and for users whose needs dictate a screw down unit, the steel can has been soldered to a 7/16'' hex stud.

Care should be taken if this unit is to be subjected to high temperatures during circuit construction. To prevent unsoldering the case from the stud, the case of the controlled rectifier should not be allowed to exceed 150°C.

The heat conducting properties of this unit do not differ greatly for the original steel can unit. And if case temperature is measured on the side of the steel can the original power rating characteristics may be applied.

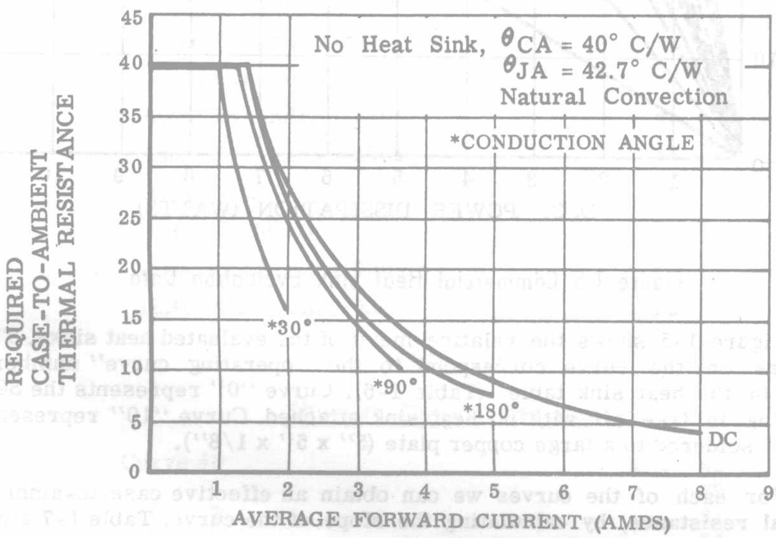

Figure 1-4 Heat Sink Thermal Resistance Requirement for TA = 25°C

USING THE MCR1304 WITHOUT A HEAT SINK

If desired, the MCR1304 may be used with no heat sink attached. Naturally, the current capability of the device is reduced. The thermal resistance, from the device to the air, is 40.0°C/W. Thus, to maintain the junction temperature below 100°C the device case temperature must still be kept below the temperature specified on the MCR1304 power rating characteristics. As shown in Figure 1-4, the maximum current capability is 1.5 amperes at an ambient temperature of about 25°C.

Commercially Available Heat Sinks

A survey of commercial heat sink manufacturers was conducted and a number of adequate heat sinks were found and evaluated.

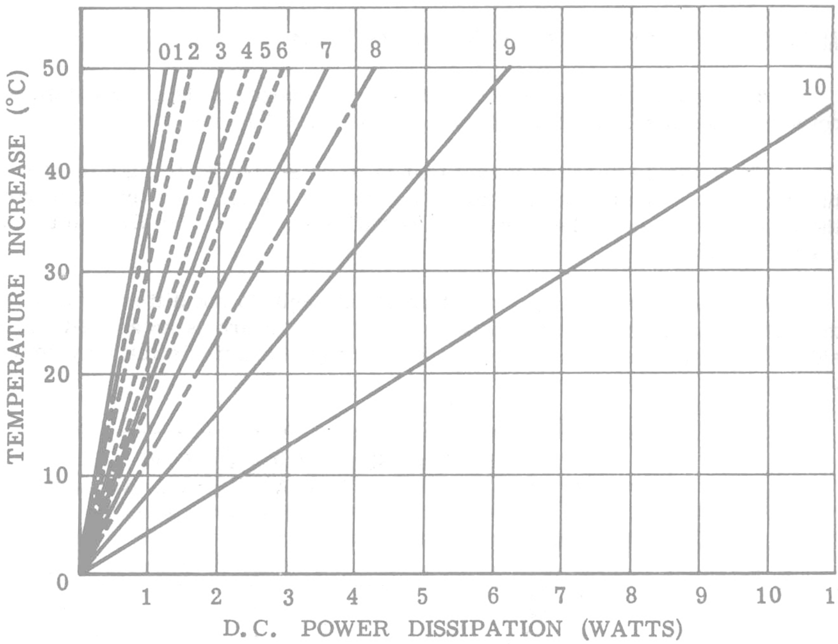

Figure 1-5 Commercial Heat Sink Evaluation Data

Figure 1-5 shows the relative merit of the evaluated heat sinks. The numbers on the curve correspond to the "operating curve" numbers listed in the heat sink table, (Table 1-6). Curve "0" represents the SCR operating in free air with no heat sink attached. Curve "10" represents the SCR soldered to a large copper plate (5" x 5" x 1/8").

For each of the curves we can obtain an effective case-to-ambient thermal resistance, by calculating the slope of the curve. Table 1-7 gives the thermal resistance for each curve.

TABLE 1-6

Manufacturer & Type No.	Operating Curve
Augat, Inc. (#9017-1P1V)	#2
Daedalus (#CS-3)	#1
Atlee Corp. (#106-707-2) with #100-236-6 clip	#1 #2
Birtcher (#3AL680)	#1
Wakefield Eng. (#NF209)	#3
Thermalloy (#2215)	#2
Relco Prod. (Series L)	#3
Staver (V2-1 (modified)	#6
Staver (V1-3)	#7
U.S. Heat Sink (#a1041)	#4
Astro Dynamics (#2703)	#6
Astro Dynamics (#2701)	#3
Astro Dynamics (#2702)	#3
Astro Dynamics (#2801)	#3
Astro Dynamics (#2802)	#5
Staver (F3-1)	#3
IERC #LP5C1B	#3
IERC #TXS on 2 x 2 plate	#7
IERC #HP3 (with TXS)	#9

TABLE 1-7

Effective Thermal Resistance

Curve #0	θ_{CA} = 40°C/W
1	37
2	31
3	24
4	20
5	19
6	17
7	14
8	12
9	8
10	4

SECTION 2

The Gate Controlled Switch

INTRODUCTION

The solid state controlled rectifier (SCR) behaves similar to the vacuum tube thyratron in that turn-off is accomplished by reversal of voltage polarity from anode to cathode. Actually, in the SCR as in other four-layer devices, turn-off is accomplished when the anode current falls below what is known as "Hold Current", hence, the voltage applied to the gate has little or no effect in turning the device "off".

The gate controlled switch (GCS) has the ability to turn off when a negative voltage of sufficient value is applied to the gate. The GCS is analogous to the type of mechanical switch which closes when pushed once and opens when pushed again. These characteristics differentiate the GCS from a power transistor, which requires a constant signal at its base to keep it "on" as well as a constant signal of opposite polarity applied to the base to keep it in the "off" condition. The GCS can also be operated as an SCR in that it can be turned off by anode-cathode voltage polarity reversal.

The turn-on and turn-off mechanism can be considered the same from the following expression for anode current:

$$I_A = \frac{I_s \pm \alpha_1 M I_G}{1 - M(\alpha_1 + \alpha_2)}$$

where I_A = anode current

I_G = gate current (+ or -)

I_s = forward leakage current

α_1 & α_2 = the respective equivalent current gains of the two transistor analogy

M = voltage multiplication factor (1 to ∞)

Obviously if the term $M(\alpha_1 + \alpha_2)$ equals the quantity "one" the anode current will suddenly avalanche and be limited only by external resistance. This can occur by the increase of "M" due to voltage or by increasing $(\alpha_1 + \alpha_2)$. At low voltages $(\alpha_1 + \alpha_2)$ is very close to unity and not much increase is necessary to initiate turn-on. Since current-gain can be increased by injecting gate current, turn-on can be easily accomplished.

However, turn-off is more difficult. The anode current equation still holds true and if gain can be decreased to a low enough value a regenerative turn-off will occur. If enough negative gate current can be applied, the gain can be decreased. Unfortunately, the amount of gate current may be quite large since the gains at high anode current approach high levels and a special method must be used to allow practical gate turn-off. Any SCR may possibly be turned-off at the gate but this is rare. The GCS is deliberately constructed to allow gate turn-off. Device engineering indicates that α_1 should be at least .95 or more and α_2 should be about .02 to achieve a turn-off gain greater than 5.

Another way of looking at this phenomenon is that increasing negative gate current increases hold current until the device turns off.

The Motorola MGCS821, MGCS-924 and MGCS-925 are gate controlled switches which have been designed to have a turn-off gain of 10 at 5 amperes.

GATE CHARACTERISTICS

The GCS static forward characteristics are the same as an SCR. The important difference is evident in the V-I characteristics of the gate-cathode terminal pair as shown in Figure 2-1.

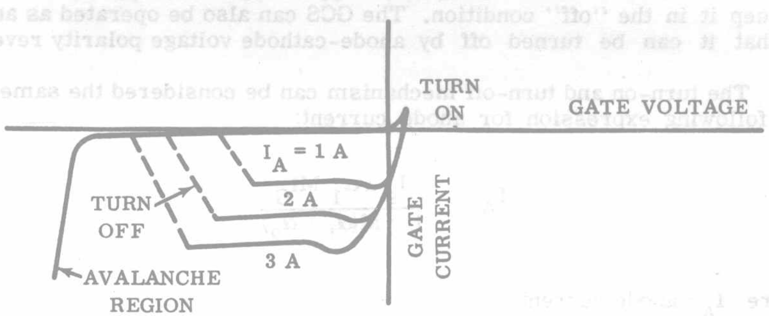

Figure 2-1 GCS Gate-Cathode Characteristics

The SCR "anode-on" gate characteristics would follow very closely the "off" characteristic of the SCR or GCS if the gate is swept with a negative voltage. However, the "anode-on" gate curve for the GCS shows a great increase in negative current and then flattens out as the applied source voltage increases in the negative direction until suddenly the curve becomes discontinuous and the operating point will jump to the off curve as dictated by the source resistance. If the source voltage is allowed to increase more the curve would trace out the avalanche region. And if the voltage is decreased with the anode off, the curve is simply the reverse characteristic of a back-biased junction.

SWITCHING TIMES

The GCS can turn-on to 5 amperes in about one micro-second. During turn-off the device exhibits storage time, fall time and hold time as shown in Figure 2-2. Gate current and gate voltage waveshapes are also shown. The source voltage was rectangular and a 10 ohm source resistance was used.

The storage time can be considerably reduced by overdriving the gate with a low "forced off" gain. This is shown in the dotted portions of Figure 2-2. To do this requires high source voltages and when the device turns off the gate operating point will be intercepted in the avalanche portion of the V-I curve. However, if the gate drive is removed within 50 microseconds or so, there will be no damage done.

The fall time is about 2 microseconds at 5 amperes anode current and the hold time may be as high as 10 microseconds although this has not been specified as yet. Overdriving does not materially decrease the fall or hold times. The significance of hold time is evident if gate signal is removed too soon the anode will switch back on. Thus, the off gate signal has a minimum applied time equal to the total forward current turn off time (storage + fall + hold) or the device reverts back to conduction, no matter how hard the off drive may be.

There are many circuits which can be used to turn off a GCS; dc, ringing choke, capacitor discharge, rectangular pulse, etc. All of these circuits must have the following qualifications, for the MGCS821, 924 &925:

1) High enough source voltage (12 volts at least to turn off 5 amperes).

2) Low enough source resistance to allow proper off current.

3) Exist in time long enough coincident with Items 1 & 2 to allow charge equilibrium (10 to 20 μsec.)

4) Low enough energy content so as not to burn out the gate. (The exact value of this has not been determined.)

An example of a capacitor discharge turn-off circuit (5 amperes) is shown in Figure 2-3.

A 2 μf capacitor is charged to 40 volts and then discharged through a 20 ohm resistor into the gate. We can see that this combination fulfills the four requirements. At the end of one time constant (40 μsec.) there will be about 15 volts and, hence 750 mA still available for turn off. In fact, the device will be completely off before one time constant. The total energy is only 1600 micro-watt-seconds and most of this will be dissipated in the 20 ohm resistor.

Inductive and rectangular pulse circuits must be designed in a similar manner. The dc circuit must be designed with Point 4 especially in mind. The pulse methods may cause the gate to avalanche but will not have enough energy to cause burn out. However, the dc or low frequency turn off circuits should avoid the avalanche mode. This is easily accomplished by using a very low (1 ohm) source resistance from a 12 volt source. The gate current will then be just a few milliamperes after turn off and no gate damage will occur.

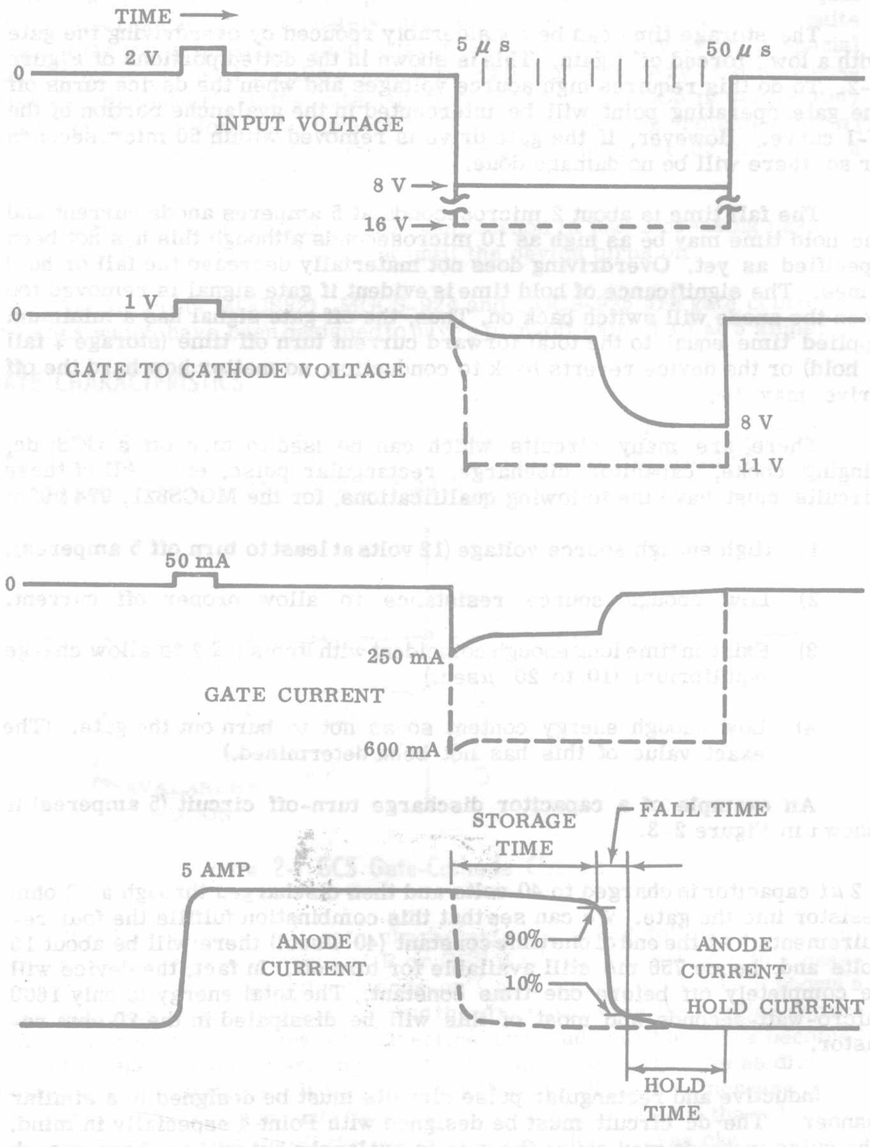

Figure 2-2 Typical GCS Switching Waveforms