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SAND--90-0736C

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Optically-triggered GaAs thyristor switches: integrated structures for environmental hardening

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ABSTRACT

Optically-triggered thyristor switches often operate in adverse environments, such as high temperature and high dose-rate transient radiation, which can result in lowered operating voltage and premature triggering. These effects can be reduced by connecting or monolithically integrating a reverse-biased compensating photodiode or phototransistor into the gate of the optically-triggered thyristor. We have demonstrated the effectiveness of this hardening concept in silicon thyristors packaged with photodiodes, and in gallium arsenide optically-triggered thyristors monolithically integrated with compensating phototransistors.

1. INTRODUCTION

High temperature and transient radiation conditions adversely affect operation of thyristor switches. High temperature reduces the breakover voltage of the thyristor by increasing the regenerative transistor gains associated with switching in the pnpn-doped structure. High dose-rate radiation can prematurely trigger a thyristor switch by the introduction of photocurrents. These adverse effects from radiation and temperature can be reduced somewhat by the use of gallium arsenide (GaAs) rather than silicon (Si), due to its larger band gap and light absorption coefficient.[1] GaAs thyristor designs, however , generally require trade-offs between radiation hardness and operating voltage.[2] As a result, there remains the need for a high-voltage, radiation-hard optically-triggered thyristor.

The basic structure and current-voltage (I-V) characteristic of a previously studied optically-triggered GaAs thyristor are shown in Fig. 1A and 1B. The layers are alternately doped n-p-n-p and they can be modelled as linked npn and pnp transistors. A third (gate) terminal is often connected to the p layer. Typical breakover voltage in the low current or 'off' state is given at 40 V in Fig 1B. It is a function of depletion width, avalanche effects, and the regenerative gain present in the n-p-n-p (or p-n-p-n) structure. To first order, the blocking layer must be low-doped to prevent avalanche breakdown at higher voltages. The layer thickness must then be large to accommodate the increased depletion layer thickness and prevent the punch-through breakdown condition.[3] We have found that when the depletion layer thickness is increased, it acts as a collector for radiation-induced charge and the radiation tolerance drops for uncompensated (two-terminal) devices.[1,2] Under conditions of light (or transient radiation) the induced photocurrent causes increased gains α_1 and α_2 in the linked transistors. When the sum of the gains reaches unity the device switches. This causes the hold-off voltage in the I-V curve to drop (to 3 V in Fig. 1B). With an applied bias between the two values, the device will switch into the high current or 'on' state.

The effects of radiation and temperature are greatly reduced by connecting a reverse-biased compensating photodiode or phototransistor into the gate terminal of an optically-triggered thyristor, as in the schematics of Fig. 2A and 2B. Without optical triggering, the gate terminal is used with a positive signal to trigger the thyristor. The use of an optical trigger, however, allows the gate to be used for these compensation elements. Under normal operating conditions, illumination from a laser diode triggers the thyristor, while the compensating element is shielded from the light. Since the gate terminal sees only a small negative leakage current, the thyristor is then essentially used as an optically-triggered two-terminal device. When the switch is exposed to ionizing radiation, the photodetector produces a negative current at the gate of the thyristor, which compensates the induced photocurrent. This prevents the switch from being triggered by transient radiation. Likewise, increased leakage in the compensator at high temperatures produces negative current on the thyristor gate. This helps offset the effects of increased regenerative gain in the thyristor.

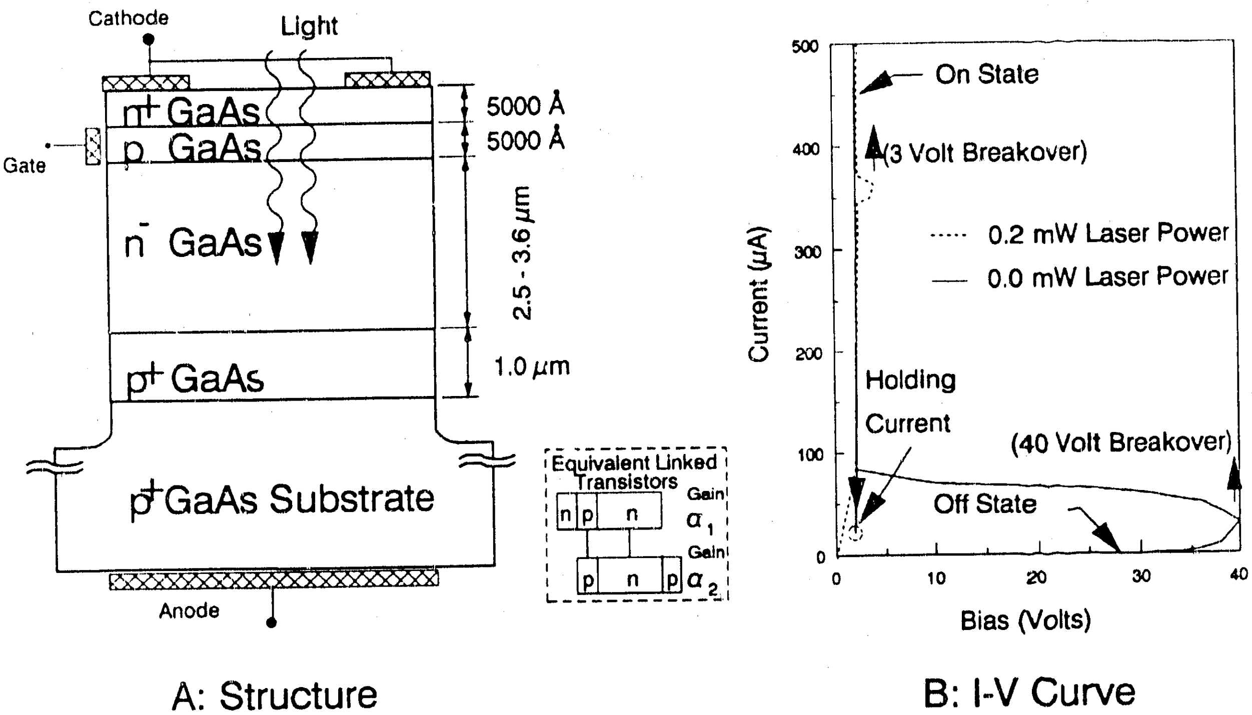


Figure 1 Structure and I-V characteristic for a GaAs optically-triggered thyristor. The equivalent linked transistor representation is in the inset.

In this work we demonstrate two methods for implementing the radiation-compensation technique. First, we harden an optically-controlled silicon thyristor to triggering by transient radiation, using a compensating photodiode as in Fig. 2A. We then show an implementation of Fig. 2B, using GaAs. In this case, the pnpn-doped thyristor is monolithically integrated with a compensating phototransistor.

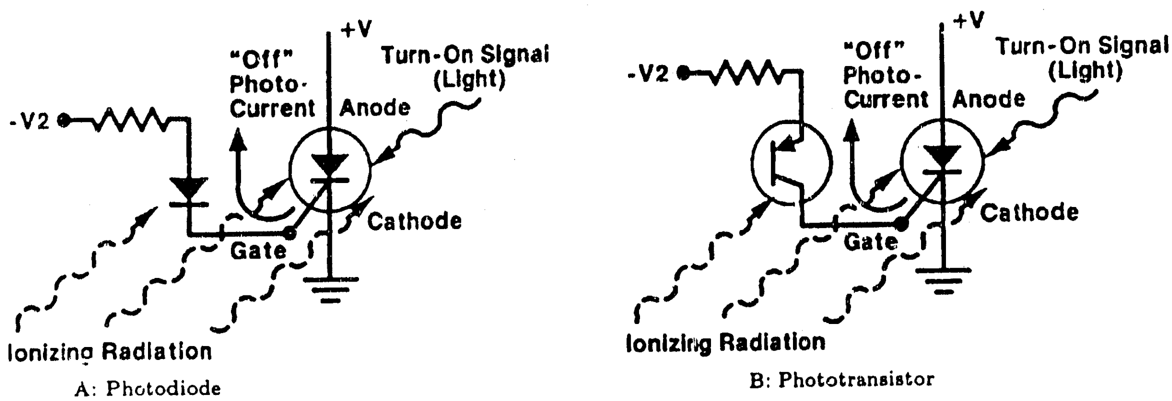


Figure 2 Compensation schematics. Reverse-biased photodetectors produce negative current on the thyristor gate in transient radiation.

2. COMPENSATION IN A SILICON HYBRID

We first tested the compensation concept, using a discrete silicon thyristor and photodiode, as in Fig. 1A. The thyristor was a three-terminal device rated at 100 V (Unitrode GA201). It was exposed to 3 ns x-ray bursts from a Febetron 706 electron accelerator. The electron output of the 600 keV machine was aimed at a tantalum target, which gave peak spectral response between 100 and 300 keV. Results from this experiment appear in Fig. 3, where the threshold radiation dose rate (required for switching) is plotted as a function of applied voltage. The area above and to the right of each threshold line represents dose rate and voltage combinations that will cause switching. With the gate of the thyristor floating, switching occurred along the lower line of Fig. 2. This response was tested up to the dark breakover level of 160 V, and the results indicate that the device is sensitive to switching above 4 x 10^9 rad(Si)/s at applied voltages greater than ≈ 10 V. At the rated value of 100 V, the device will switch in any radiation environments having dose rates greater than 2 x 10^8 rad(Si)/s. Note that these results were obtained with a 3 ns radiation pulse. This pulse length is considerably less than the carrier lifetime (which we measured to be at least 50 ns and can be as much as 2.5 ms in intrinsic Si).[4] Thus, the cumulative dose effects at longer pulse lengths would make the uncompensated device even more sensitive to switching at a given dose rate.

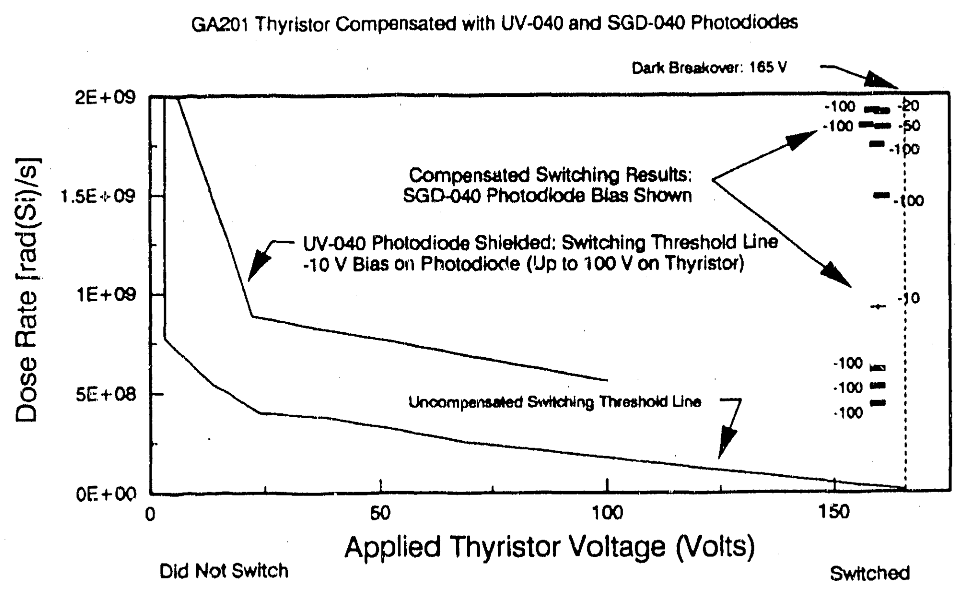


Figure 3 Radiation test results for compensation in a silicon thyristor connected to discrete photodiodes.

Various negative currents were then applied to the gate of the thyristor during testing. We found that as little as -1.0 μA into the gate would inhibit switching up to our maximum obtainable values of 100 V and 1 x 10^9 rad(Si)/s. Next, an EG&G UV-040 Si photodiode was connected to the gate of the thyristor in the configuration of Fig. 1A. When it was biased at -10 V through 50 Ω, switching was again inhibited up to 100 V and 1 x 10^9 rad(Si)/s. The biased photodiode was then shielded with a 19 mm thickness of lead and its photocurrents were measured. In this condition, it would not produce more than about 0.28 mA (peak) during the radiation pulse. Thus, it was mainly the negative leakage current on the photodiode that flowed from the gate of the thyristor (≈ 50 nA). The device then switched along the upper curve in Fig 2 (up to 100 V). In this case, dose rates above 7 x 10^8 rad(Si)/s switched the thyristor at applied voltages greater than 20 V. Thus, the leakage currents alone could not account for the radiation compensation in this device configuration.

Finally, an EG&G model SGD-040 photodiode was connected to the GA201 thyristor. This device was biased at various levels during exposure as in Fig. 3. At all bias levels greater than -10 V, the photodiode inhibited switching at the maximum applied bias of 160 V, even at 2 x 10^9 rad(Si)/s. Thus the photodiode was extremely effective at inhibiting radiation-induced switching.

As stated above, the sensitivity to radiation-induced switching would be even worse for the uncompensated thyristor at longer pulse lengths with the same dose rate, due to the cumulative effects of total dose. This is not a fundamental limitation for the case of the compensated device arrangement, since the negative photocurrent at the gate of the thyristor flows for the entire length of the radiation pulse. We verified this for the SGD-040 photodiodes in the Febetron. At 4.43 x 10^8 rad(Si)/s, the peak photocurrent for the SGD photodiode (biased at -100 V) was 200 mA. In addition, this radiation photocurrent exhibited an exponential tail that was still above 1 mA a full 1 μs beyond the end of the radiation pulse. This photocurrent tail is important for the prevention of the delayed switching that we have often observed in thyristor devices and have modelled, along with the effects of transient radiation in GaAs thyristors.[2]

The GA201 thyristor itself was easily switched by light from an 800 nm laser diode. Optical powers as low as 20 mW for 200 ns could switch the device, though with some delay in switching. Above 80 mW, switching delays were circuit limited. Peak currents switched were in excess of 150 A for 0.5 μs.

3. FABRICATION AND OPERATION OF A COMPENSATED GaAs THYRISTOR

The compensation scheme of Fig. 2B can be realized in GaAs, using the device structure of Fig. 4. Here, epitaxial p-n-p-n layers form the thyristor and compensator. Ohmic metallizations are shown by the diagonally-hatched regions. The p-doped $Ga_{.7}Al_{.3}As$ layer forms an etch stop for the selective dry and wet etch techniques that separate the two devices. The thyristor is the inner device, as indicated by its optical opening and positive bias. The outer ring is biased with a negative voltage to act as a pnp phototransistor. The p-doped GaAs layer that forms the gate of the thyristor also acts as the emitter on the compensating pnp phototransistor. Depletion regions under bias are shown by shaded regions and radiation-induced photocurrent paths are shown, along with the primary path of the desired compensation current (the dashed arrow). The blocking layer is doped at 6 x 10^{15} cm^{-3} so that avalanche breakdown will be high. Because of the low doping, the depletion region formed at the reverse-biased p-n^- junction grows quickly with bias. Thus, the blocking layer is made 6.0 μm thick. This produces a device with a breakover voltage above 60 V. Without compensation, however, it will be very sensitive to radiation-induced switching.

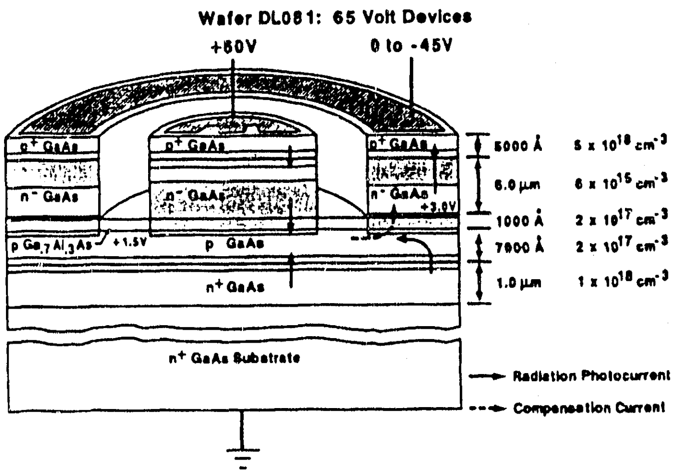
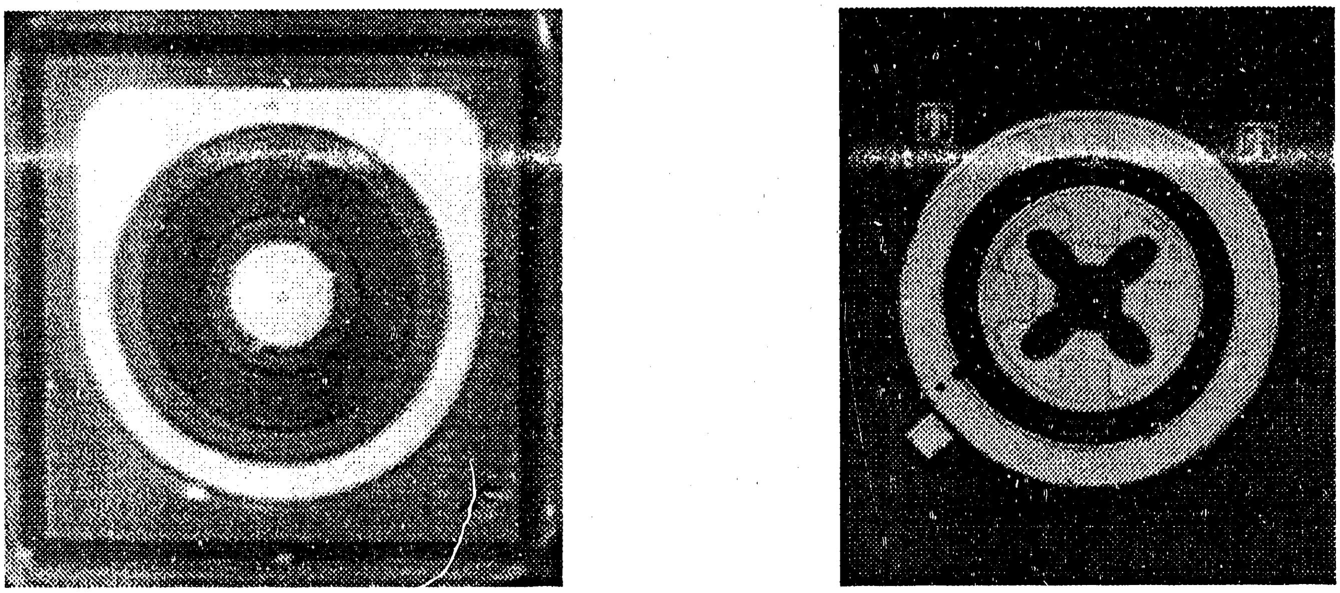


Figure 4 Cross-section of the integrated GaAs structure. Shaded areas are depletion regions at the applied voltages. Hatched areas are the metal contacts. Photocurrents are shown by the arrows.

Note in Fig. 4 that the base of the compensating pnp phototransistor is formed by the n- blocking layer. As we build thicker devices with higher breakover voltages, a correspondingly higher bias can be placed on the compensator. This allows us to adjust the gain of the pnp phototransistor to increase the compensating photocurrent in a radiation environment. We can then achieve transient radiation tolerance, even with the increased depletion layer width associated with high-voltage operation. This effect will be demonstrated shortly.

The compensated GaAs thyristor of Fig. 4 was built using two patterns as in Fig. 5A and 5B. The first pattern (Fig. 5A) allowed us to test the basic compensation mechanism by exposing both the thyristor and compensator to light. In this pattern, each of the devices is only partially covered by the ohmic metal, as indicated by the light circle and ring patterns. The annular "trench" etch that separates the two devices appears between the two metal patterns. The bottom of this trench is the Ga_7Al_3As layer of Fig. 4. The dark square outline shows the mesa etch pattern that forms the outer edge of the compensator. This square mesa is 2 mm on each side.



A: Light Can Strike Thyristor and Compensator

B: Light Can Only Strike Thyristor

Figure 5 Top views of two monolithic implementations of the compensated thyristor in GaAs material. The darker annuli are the etched trenches. Lighter areas are metal contacts.

The design of Fig. 5B is similar to that of 5A, but metal covers the entire outer ring that forms the compensator. It is a direct realization of Fig. 4, where an optical opening appears in the metal pattern of the inner device. Thus, while the inner (thyristor) device can be easily triggered by light, the outer compensator is exposed only to radiation. Again, the annular etched trench separates the two devices. Both the thyristor and compensator have approximately the same area. This pattern was fabricated in several different scaled sizes. For devices that were radiation-tested, the inner thyristor had a diameter of 446 μm.

Two sets of experiments were carried out to demonstrate device behavior in radiation environments. First, current-voltage characteristics of the device in Fig. 5A were measured using light as the radiation source. Experiments with light allow characterization under continuous radiation, but have the disadvantage that the dose rates are relatively small (equivalent to about 1×10^8 Rad(Si)/sec) and the absorption is spatially nonuniform. Second, the switching conditions were determined for applied x-ray pulses from the Febetron. The two experiments provide not only dose rate hardness levels, but show detailed mechanisms for the radiation response of the monolithic structure.

Figure 6 shows three I-V curves for the compensated thyristor switch, corresponding to (a) dark I-V, (b) I-V with light only illuminating the thyristor area of the switch, and (c) I-V with light illuminating the entire structure, both the thyristor and the transistor, as in Fig. 5A. The light was from an 800 nm laser diode, and the thyristor curves were generated in a current-source mode using a Hewlett-Packard 4145B semiconductor parameter analyzer. The compensator was biased at -35 V.

In the dark, as in curve (a), the switch exhibits conventional thyristor behavior with a breakover voltage of about 50 V. When the thyristor alone is exposed to a few milliwatts of light as in (b), the high conductance or "on" state is exhibited. Finally, when both devices are illuminated, a "conventional" characteristic is recovered (curve(c)). The breakover voltage for (c) is slightly reduced and the current value at breakover is increased due to photocollection. In this case, the thyristor qualitatively behaves as if it were in the dark, since it still holds an applied bias in a low current "off" condition. Thus, the thyristor has become insensitive to the applied radiation, due to the action of the compensating phototransistor.

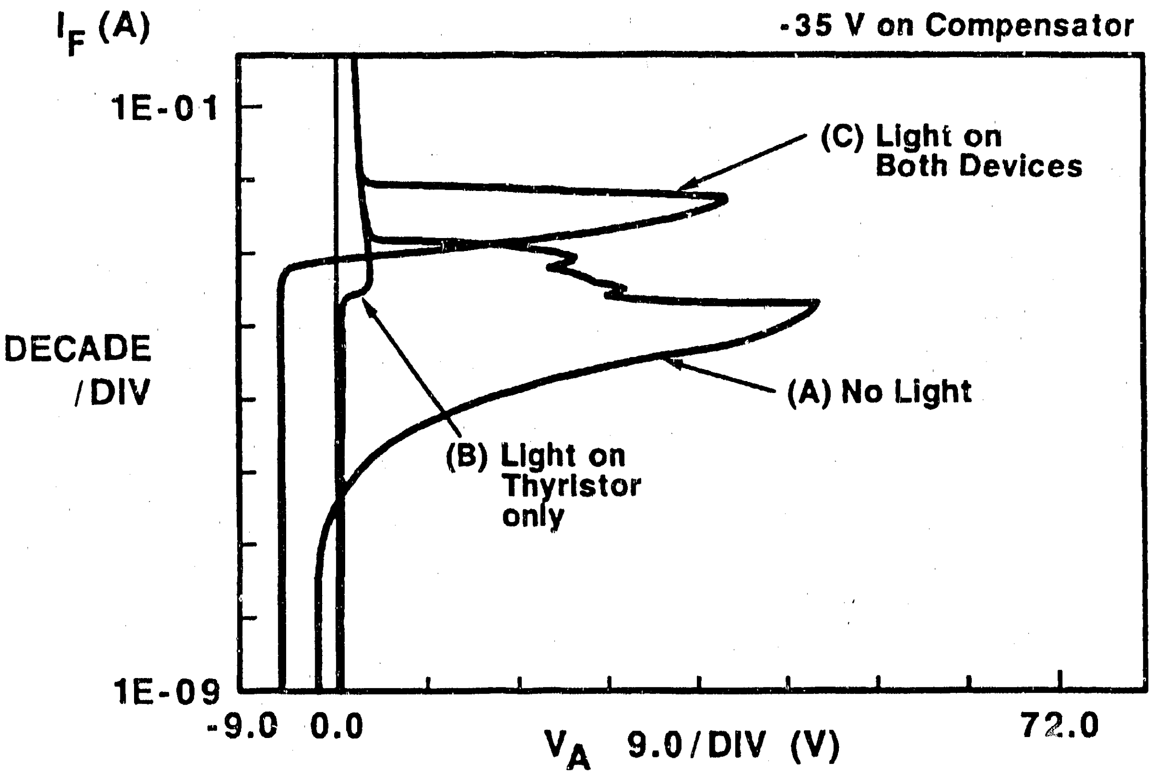


Figure 6 Current-voltage curves demonstrate compensation in an integrated GaAs thyristor. In curve (c), the compensator is active. For (b), light strikes only the thyristor and the compensator is inactive. Curve (a) shows the dark breakover voltage.

The curves of Fig. 6 clearly show the mechanism by which radiation is compensated. Recall that light-induced (or radiation-induced) switching proceeds by a mechanism of regenerative feedback in the linked transistors that make up the thyristor. As compensation current is applied to the npn portion of the thyristor (along the p-doped base region of Fig. 4), it reduces the gain of that transistor. The application of compensating current to the base of this transistor is particularly effective, since it has a thinner base and thus a higher gain than its pnp counterpart in the thyristor (Fig. 4). If the sum of transistor gains α_1 and α_2 do not reach unity then the regenerative feedback loop that causes switching will not form. Thus, even though there is a photocurrent in the device as in curve (c) of Fig. 6, the device will hold off voltage without switching to the high-current state.

4. RADIATION RESPONSE IN THE INTEGRATED GaAs STRUCTURE

The radiation dose-rate tolerance for compensated GaAs thyristors with the structure of Fig. 4 was determined by exposing the devices to 3 ns radiation pulses from a Febetron 706, as was previously done for the Si thyristors. Various negative bias levels were placed on the compensator, and its effectiveness at preventing radiation-induced switching was verified as in Fig. 7. Again, the threshold radiation dose rate (required for switching) is plotted as a function of applied voltage. The area above and to the right of each threshold line represents dose-rate and voltage combinations that will cause switching. When no bias was applied to the compensating phototransistor, its gain was very low. In this case, very little compensation current was induced on the thyristor gate, and the device was extremely sensitive to radiation-induced switching. All applied thyristor bias levels greater than 10V caused switching at only 6 x 10^8 rad(Si)/s.

Threshold radiation levels for switching at a given applied voltage are greatly increased with negative applied compensator bias. A larger bias on the phototransistor increases its gain, which corresponds to a greater compensation current at the thyristor gate. With a 45 V reverse bias on the compensator, the thyristor was able to hold off 2 x 10^9 rad(Si)/s with a 40 V applied forward bias. This represents nearly an order of magnitude increase in radiation tolerance over the unbiased (uncompensated) case. Thus, we have shown that compensation is effective in a monolithically integrated GaAs structure.

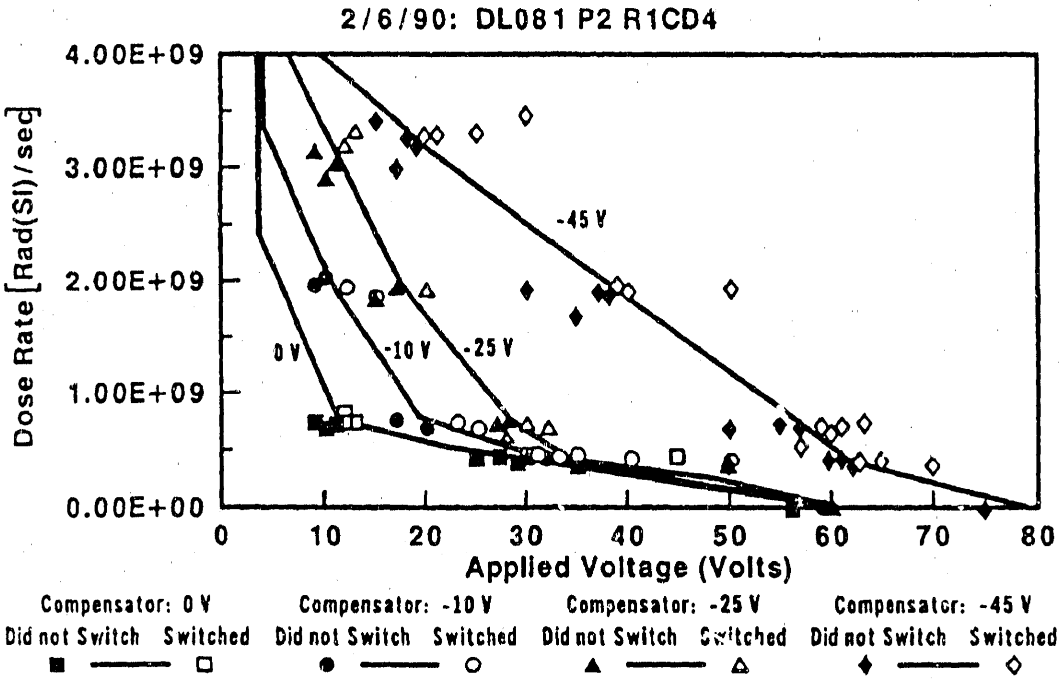


Figure 7 Increased tolerance to switching by transient radiation when higher bias increases gain in the compensating phototransistor.

Note in Fig. 7 that the -45 V compensator bias also increased the dark breakover level of the thyristor from 60 V to 80 V. This occurred because leakage currents limited the breakover level of the thyristor. Without compensation, regenerative feedback was induced in the thyristor above 60 V, due to the combined action of transistor gain and leakage currents. When -45 V was applied to the phototransistor, there was enough leakage in that structure to induce a slight compensation current on the thyristor gate. This caused the gain of the pnp portion of the thyristor to drop, and the dark breakover level rose. It follows that compensation might be used to stabilize breakover in leaky thyristor structures. This will be discussed further in terms of temperature compensation.

Note that the addition of the compensator improved the radiation tolerance of the Si thyristor more than it did in the GaAs device. This is due to the fact that the compensated GaAs thyristor is not optimized. There are several things that can be done to optimize the integrated structure in GaAs. First, the gain and area of the compensating phototransistor can be adjusted. We have already shown how the phototransistor gain is affected by bias. Gain in the compensator could be also be modified by techniques such as implants. Greater area would increase the overall compensation current.

Another major factor limiting compensator performance is spreading resistance in the p-type GaAs thyristor gate layer. This layer is relatively thin and the compensating current must travel a large lateral distance as in Fig. 4. The resistance encountered will tend to limit the effectiveness of the compensation current. Furthermore, the compensating current must reach under the entire surface of the thyristor. Thus, even if the distance between the thyristor and compensator is small, the compensation may be ineffective at the center of the thyristor, unless the device is small or is designed with an interleaved compensator, such that all points within the thyristor are within a certain distance of the compensator. This technique is often used to improve the response of gate electrodes in conventional thyristor switches.[4]

Another factor that may presently limit the effectiveness of the integrated compensator is the parasitic junction at the p-n^+ (base-substrate) interface. Because all of the bias is dropped across the blocking layer, this junction is essentially zero-biased. It then acts as a photovoltaic junction as denoted in Fig. 4 by the +1.5 V potential in the p-type quasi-neutral region. In a radiation environment, this junction will generate current that opposes the desired compensation current. This effect can be reduced by shorting the junction at the outer edge of the compensator, or placing a heterojunction barrier in the structure, as in previous radiation-hardened photodiode designs.[5]

5. COMPENSATION FOR ELEVATED TEMPERATURE

The radiation compensation technique described above is also useful for extending the operating temperature range of thyristor switches. We have applied the technique to discrete Si devices (Fig. 2A) and to integrated structures in GaAs (Fig 2B). Without compensation, the transistor gains and leakage currents within the thyristor rise with temperature. It follows that breakover voltage will be reduced as temperature goes up. This can greatly limit the usable operating voltage at higher temperatures.

When the reverse-biased compensator is connected to the gate of the optically-triggered thyristor, its leakage also goes up with temperature. This lowers the gain in the npn portion of the thyristor and helps to keep the breakover voltage from dropping as temperature rises.

We first tested the effectiveness of the temperature compensation technique using a GA201 Si Thyristor and a UV-040 Photodiode, connected as in Fig. 2A. We elevated the ambient temperature while testing for maximum breakover voltage, for various values of photodiode bias. The results appear in Fig. 8. Note that with no compensation (Gate Floating), the breakover voltage has fallen to its rated value of -100 V at a temperature of + 75 °C. Compensation is partially effective with a -10 V bias on the photodiode, but the leakage current does not rise quickly enough with temperature to completely stabilize breakover voltage on the thyristor. At -25 V, the leakage current rises significantly with temperature ($\approx 7\ \mu A$ at + 75 °C). It then stabilizes the breakover level around 160 to 170 V. This is approximately the optimal amount of leakage. We do not want more than a few microamperes negative current on the gate of the thyristor, however, or its switching characteristics will suffer increased delays.

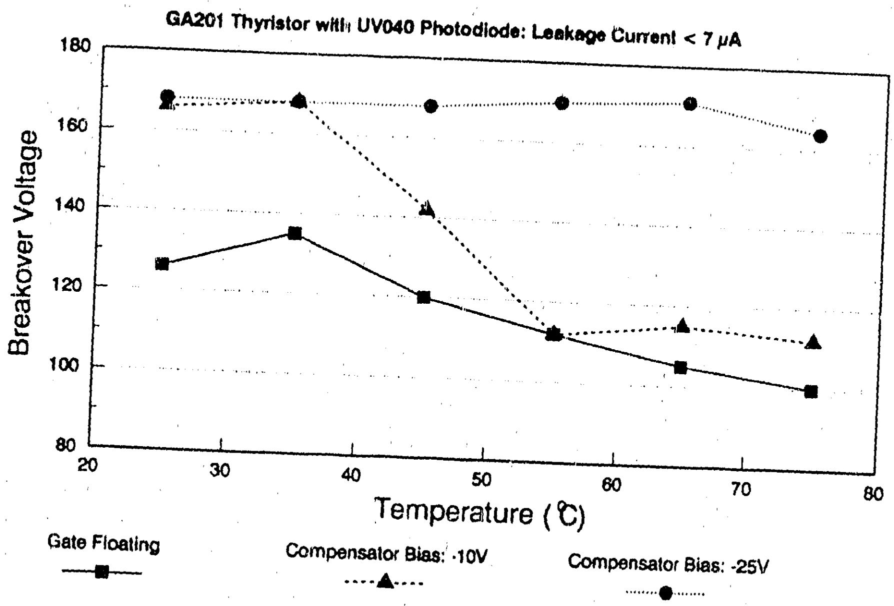


Figure 8 Temperature response of a GA-201 Si thyristor with various negative bias levels on the compensating UV-040 photodiode.

Temperature stability is very poor in the two-terminal GaAs thyristor of Fig. 1A. These results appear in the curves of Fig. 9. Here the constant-current I-V response shows that breakover voltage drops as temperature goes up. At only 55 °C, the device will no longer hold off voltage. Note that the current at breakover does not change. This clearly indicates that the internal gains within the thyristor rise with temperature, and that compensation is needed.

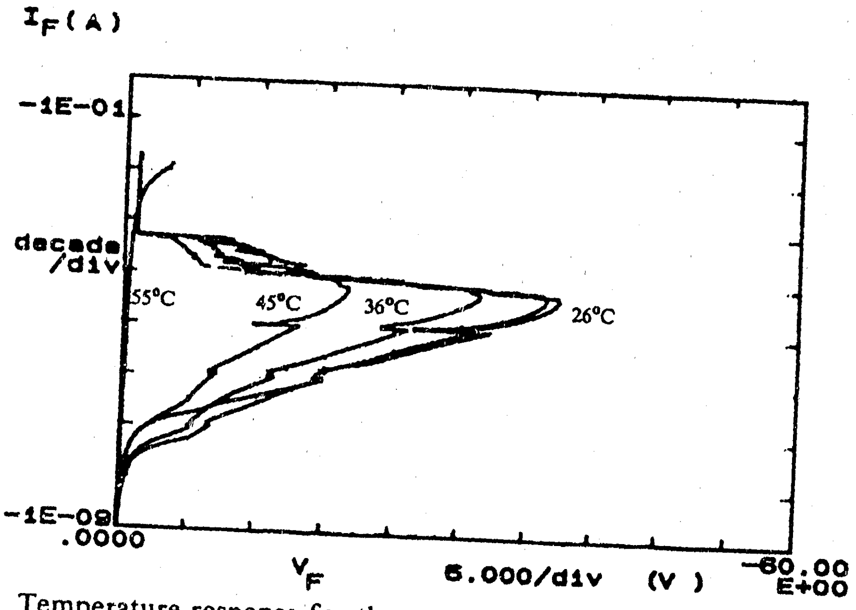


Figure 9 Temperature response for the two-terminal (uncompensated) GaAs thyristor of Fig. 1A. Note that maximum breakover is very sensitive to temperature.

The lack of temperature stability in the two-terminal GaAs thyristor is in sharp contrast to the stability obtained with compensation in the integrated GaAs device structure. The results of this experiment are summarized in Fig. 10. Here, the I-V curves for both the thyristor and compensator are traced out as a function of thyristor voltage (in the lower left corner of the figure). Again, the 4145B parameter analyzer is used in a current-controlled mode. Compensator bias is -10 V as shown. Since these curves are difficult to read, the results are summarized in the upper region of Fig. 10. Note that the breakover voltage remains approximately constant with temperature. The off-state leakage current in the thyristor actually drops as temperature rises, due to gain in the npn portion of the thyristor multiplying the increased negative compensation current. Thus, the integrated compensation structure of Fig. 4. is effective at stabilizing breakover voltage at elevated temperatures.

Temperature (°C)	Breakover Voltage (V)	Current (µA)	Compensation Current (nA)
25	66	20	-250
35	64	20	-300
45	63	25	-419
55	54	5	-465
65	60	2.5	-619
75	57	2.5	-719

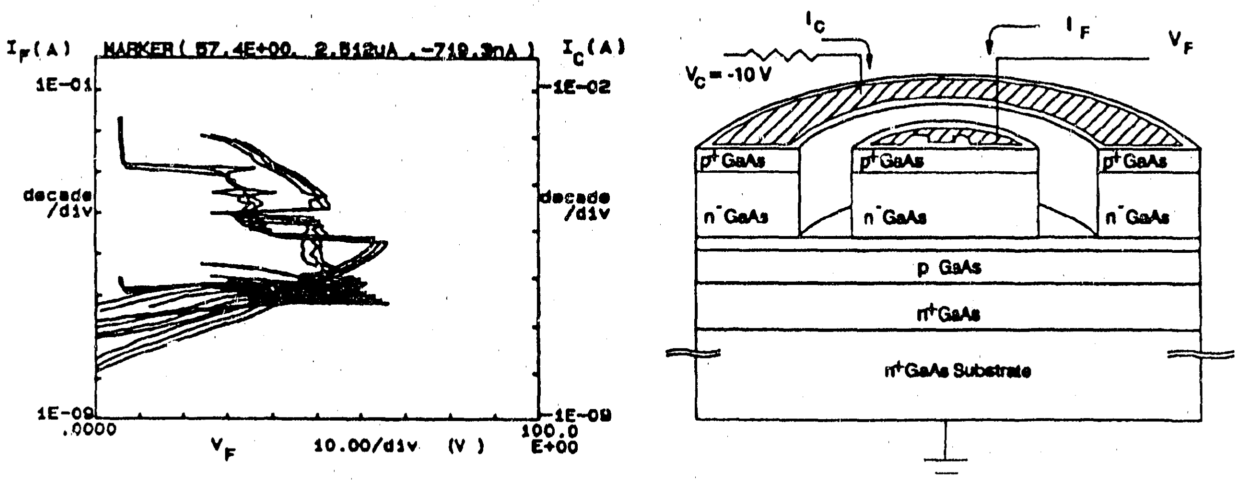


Figure 10 Increased temperature stability for the GaAs compensated thyristor of Fig. 4. Results from the plotted I-V curves are summarized in the table above.

6. SUMMARY

We have shown that the addition of reverse-biased compensating photodetectors can improve the environmental performance of optically-controlled thyristors. This technique can be applied to both discrete silicon and integrated GaAs devices. Using compensation, we can provide greatly increased tolerance to switching by transient radiation, and breakover voltage stability at elevated temperatures. Our present integrated GaAs structures have been realized in epitaxial materials, where all the layers are grown on a highly conductive substrate. This is suitable for low-voltage applications, but has limited applicability for high-voltage (>100 V) structures. Other researchers have investigated GaAs thyristor structures for high voltage, where the entire substrate forms the blocking layer.[6] Monolithically integrated or hybrid compensators can also be applied to these high-voltage structures to extend operation into transient radiation and high-temperature environments.

7. Acknowledgements

The authors would like to thank John Joseph, Mark Jenkins, and Glen Knauss for aid in device fabrication and testing. This work was performed at Sandia National Laboratories for the United States Department of Energy under Contract DE-AC04-76DP00789.

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