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RADIATION RESPONSE OF OPTICALLY-TRIGGERED GaAs THYRISTORS

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Abstract

Gallium arsenide optically-triggered thyristors that exhibit tolerance to high x-ray dose rates have been fabricated. These two-terminal epitaxial devices feature breakover voltages of 18 V to 38 V with no radiation. They trigger at less than 2 volts with only tenths of mW of laser light, but do not trigger at 2 x 10^9 Rad(Si)/s with a bias level as much as 40 to 60 percent of the zero-radiation breakover voltage. When these devices are bombarded with neutrons, the reduced carrier lifetimes result in a decreased sensitivity to triggering by light and ionizing radiation.

I. INTRODUCTION

In radiation environments, optically activated switches offer potential advantages in safety, reliability, and resistance to electromagnetic pulse and interference effects compared with conventional electronic devices. Such advantages are particularly apparent when the switch is contained in a shielded case and is triggered directly by an optical input signal carried through the shield-wall along a non-conductive fiber-optic path.

Radiation-induced switching, however, is a well-known phenomenon [1]. For applications that involve exposure to high dose rates of ionizing radiation, this switching must be prevented by a hardened version of the light-activated switch. The ability to trigger reliably on a given pulse of light, yet resist switching on exposure to a high dose rate of ionizing radiation constitutes hardness for such a switch. This hardness is increased by (1) absorbing light spatially near a collecting junction and (2) reducing carrier diffusion lengths to suppress collection of the spatially uniform charge generation associated with a radiation pulse. Both of these features are enhanced by the use of GaAs instead of Si as the material for the switching device.

A. Advantages of GaAs over Si

In Si devices, the diffusion lengths are long (compared to GaAs), due to the relatively long lifetimes in the material. Optical absorption depths are also less in Si, due to the indirect band gap. Because of the shorter diffusion lengths in GaAs, less of the radiation-induced carriers in the neutral regions of the device will be collected by the junctions. The stronger absorption coefficient in GaAs allows the same photocurrent to be generated from a given light pulse, using a thinner active region than in a Si device. These effects were exploited in earlier work to make hardened photodiodes, where the III-V based devices were some 40 times harder to transient radiation than common Si devices [2].

The uniform absorption of energetic photons causes a relatively large photocurrent density at the reverse-biased junction of a Si thyristor, due to the large volume of material within a distance of one diffusion length. This results in a high sensitivity to radiation-induced triggering. In a GaAs thyristor however, carriers must be generated within several μm (one diffusion length) of the reverse-biased junction in order to add to the radiation-induced photocurrent density. It follows that a GaAs thyristor should be inherently harder to transient radiation than a silicon device with a similar active region thickness.

GaAs also has an advantage over Si in that the short carrier lifetimes lead to an increase in the switch-off speed of the thyristor. During the on-state switching transient, GaAs has the advantage of a regenerative mechanism that speeds switching; light generated during switching aids the process [3].

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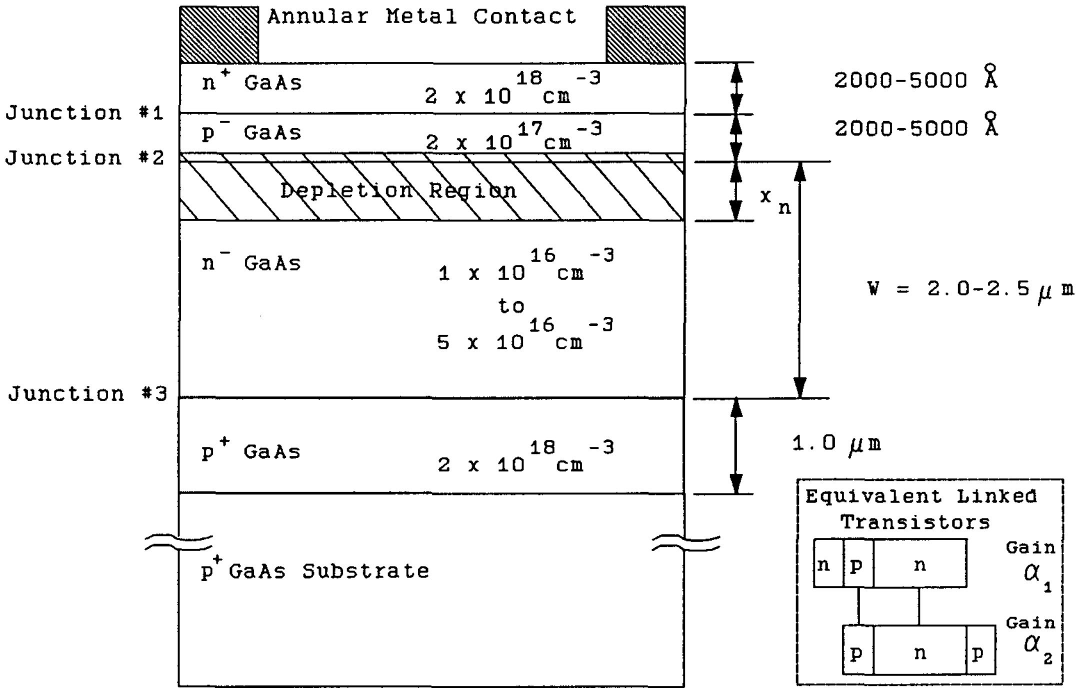

Fig. 1. Cross-sectional structure of the GaAs thyristor device. Note the equivalent linked transistor structure in the inset.

B. Arrangement of this Work

In this paper, we discuss the design, fabrication, and testing of GaAs light-activated thyristors. Basic operational and design principles are used to establish breakover voltage limits on the GaAs thyristor devices. Results for several device designs are then presented. Test results from neutron irradiation of existing devices are also presented and device area issues are discussed.

II. THYRISTOR PRINCIPLES

A. Basic Operation

The basic thyristor structure consists of n^+, p^+, and n^- doped layers grown by molecular beam epitaxy on a highly doped p type substrate (Figure 1). When a negative voltage is applied to the n^+ layer, junction 2 is reverse-biased, while junctions 1 and 3 are forward biased. Thus, very little current flows as in the "off-state" region of Figure 2. With increasing voltage, a point is reached ("breakover voltage" in Figure 2) where sufficient current flows to collapse the reverse-biased junction, inducing "on-state" operation. This on-state persists as long as the current is maintained above a specific value (the holding current). The transition or breakover voltage phenomenon is triggered by the mechanisms of avalanche, punch-through, and/or an increase in the gains of the linked n-p-n and p-n-p transistors that form the thyristor structure (Figure 1, inset).

B. Design Considerations

Because the n^- blocking layer is doped at a relatively low level, the depletion width x_n in the layer grows quickly with applied voltage V_a

$$x_n = \left(\frac{2\epsilon(V_{bi} - V_a)N_A}{q(N_A + N_D)\ N_D} \right)^{1/2} \qquad (1)$$

where N_A and N_D are the doping levels on each side of the p^+/n^- reverse-biased junction in the thyristor structure (respectively). Permittivity ϵ is the total permittivity for the GaAs material, q is the unit charge, and V_{bi} is the doping-dependent built-in voltage for the junction, which for our GaAs devices ranges between 1.2 and 1.4 volts [4]. If the doping of the n^- blocking layer is low, then the width of that layer must be relatively wide in order to prevent punch-through (where x_n = layer width W). Thick layers are relatively undesirable from the point of view of radiation tolerance however, due to the fact that the larger material volume may produce a larger photocurrent density. This imposes a fundamental trade-off between increased breakover voltages and radiation tolerance.

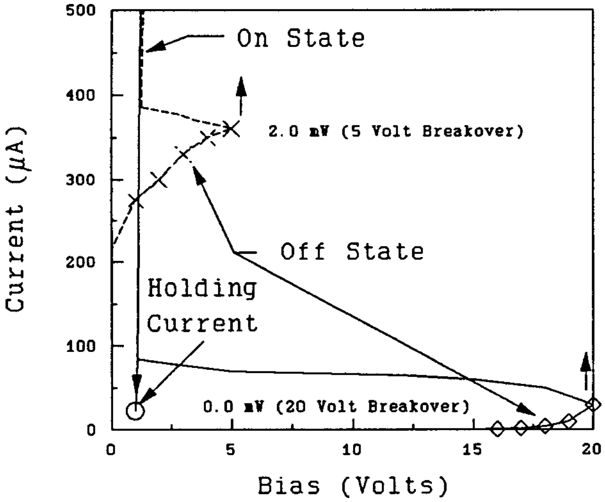

Fig. 2. Current versus voltage for the GaAs thyristor device as a function of quoted optical illumination. Note on-state and off-state regions of operation.

If N_D is doped at too high a level, then the breakover voltage will be limited by the avalanche breakdown condition, given by

$$V_{avl} = 60 \left(\frac{E_g}{1.1} \right)^{3/2} \left(\frac{10^{16}}{N_B} \right)^{3/4} \quad (2)$$

where N_B is approximated as effective doping N_{eff} (such that $1/N_{eff} = 1/N_A + 1/N_D$) and E_g is the GaAs band gap energy [5].

It follows that an effective first-order design for minimum volume or maximum radiation tolerance is to adjust doping in the n^- blocking layer such that the avalanche voltage equals the punch-through voltage. This condition is represented in Figure 3, which shows the depletion depth (or minimum required n^- layer thickness) as a function of doping (or avalanche voltage). In practice, actual breakover voltages are lower than this upper-bound level, due to the effects of saturation, generation, and localized leakage currents on the gains of the linked transistors in Figure 1.

C. Linked Transistor and Photon Triggering

The linked transistor model can also be used to describe the influence of light or ionizing radiation on the breakover characteristics of the thyristor. If we assume that the reverse breakover limit on junction 2 in Figure 1 is much larger than the forward voltage drops on junctions 1 and 3, then the terminal voltage on the thyristor is close to the reverse voltage on junction 2, given by

$$V_2 = \frac{kT}{e} \ln\left[1 + \left(\alpha_1 + \alpha_2 - \frac{1}{M_2}\right) \frac{I}{I_{2s}}\right] \quad (3)$$

where k is Boltzman's constant, T is temperature, α_1 and α_2 are the small-signal gains of transistors 1 and 2, M_2 is the avalanche multiplication factor at junction 2, and I_{2s} is the reverse saturation current at the junction [6]. Because M_2 is a function of V_2 and α_1 and α_2 are functions of current I, then equation (3) must be solved numerically in order to model the device, as has been done recently for these GaAs structures [6]. Note that breakover occurs when

$$\alpha_1 + \alpha_2 = \frac{1}{M_2}. \quad (4)$$

For the case where junction 2 is in reverse bias, M_2 is given by the relation

$$M_2 = \frac{1}{1 - \left[\dfrac{V_2}{V_{avl}}\right]^m} \quad (5)$$

where m is a constant that depends on specific material conditions. When the condition of

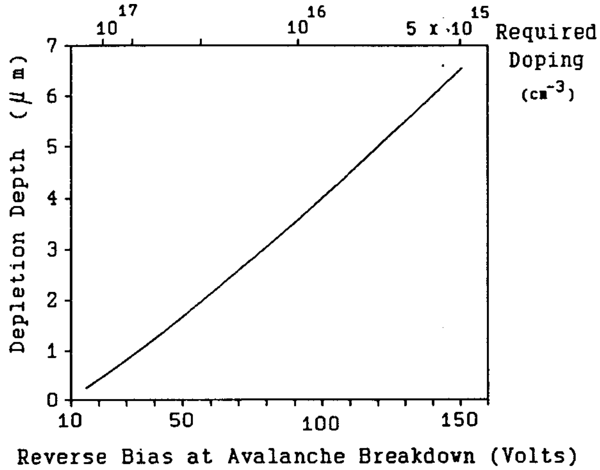

Fig. 3. Minimum calculated depletion depth at applied reverse voltage with n^- layer doped for given avalanche breakdown.

equation (4) is applied to Equation 5, then the breakover voltage is given by [7]

$$V_{BO} = V_{avl}[1-(\alpha_1 + \alpha_2)]^{1/m} . \quad (6)$$

It follows that for the physical case of an avalanche-limited thyristor, the actual breakover voltage will be equal, or (with nonzero transistor gains) less than the avalanche voltage. The condition of $\alpha_1 + \alpha_2 = 1$ approximates a low-value breakover voltage (zero in the idealized form of Equation 6). Because this condition can be satisfied by conditions other than avalanche breakdown, the magnitude of V_{BO} is often much lower than that of V_{avl}.

When light or radiation impinges upon the device, the small-signal current gains are raised by the injection of carriers and the breakover voltage of the thyristor is reduced, as in Equation 6. If the induced photocurrent is large enough, then $\alpha_1 + \alpha_2 = 1$ and the device breakover voltage is very low and independent of the value of V_{avl}.

It follows that if a voltage source is applied to the thyristor at some point below the maximum breakover point, then the introduction of enough carriers by light or ionizing radiation will raise the linked transistor alpha values, causing the breakover voltage to be moved below the operating voltage. The device then triggers into the "on" state. Again, it is desirable to minimize the radiation effects by minimizing collection volume for uniformly absorbed gamma-ray photons.

III. FABRICATION AND LASER TRIGGER TESTS

A. Device Fabrication

Devices constructed for this study were mesa-isolated, four-layer structures with ohmic contact metallization. The top-surface contacts were annular in order to allow light from an optical fiber into the epitaxial layers. Mesa areas were varied from 0.11 mm^2 to 2.24 mm^2. Layer thicknesses and doping levels were adjusted as described above to yield devices with several ranges of breakover voltage (See Table 1). Note that the breakover voltages were always less than the avalanche or punch-through limits. For lots G0004 and G0037, this was probably due to the non-zero transistor gains limiting breakover as in Equation 6. For BE031, the lower breakover voltage can be attributed to a raised transistor gain in the pnp portion of the device. This is because of an effectively smaller transistor base; the large depletion region makes the charge neutral part of the n^- region thinner as the voltage approaches the punch-through condition.

Table 1. Design and Fabrication Parameters for GaAs Thyristors

Wafer Lot	BE031	G0003	G0037
Doping: $(cm)^{-3}$			
Layer 1 (n^+)	1×10^{18}	1×10^{18}	1×10^{18}
Layer 2 (p)	2×10^{17}	2×10^{17}	2×10^{17}
Layer 3 (n^-)	1×10^{16}	5×10^{16}	1.5×10^{16}
Layer 4 (p^+)	1×10^{18}	1×10^{18}	1×10^{18}
Thickness (μm)			
Layer 1 (n^+)	0.2	0.5	0.5
Layer 2 (p)	0.2	0.5	0.5
Layer 3 (n^-)	2.0	2.5	2.5
(Layer 4 is 1 μm of p^+ material on a p^+ substrate)			
Maximum Dark Breakover Voltage (V)	21	19	38
Calculated Punch-Through Voltage (V)	27	270	68
Calculated Avalanche Voltage(V)	91	31	68
Avalanche (A) or Punch-Through (PT) Limited	PT	A	A/PT

Test results indicate that localized leakage paths also play a large role in reducing breakover voltages. Current densities are typically large in localized defect areas, compared to the remainder of the device. Current gains on the linked transistors rise with current density and device breakover occurs locally. The breakover region then tends to spread through the remainder of the device. In our larger devices, these localized effects were often dominant.

B. Laser Trigger Tests

The I-V characteristics of our devices were tested by the use of a Hewlett Packard 4145B Semiconductor Parameter Analyzer operating in a current-controlled mode. As the current to each device was ramped from zero to 40 mA, the device terminal voltage was measured, while the device surface was illuminated with a laser diode connected to an optical fiber. As laser power was increased, the device breakover voltage would decrease as in Figure 4.

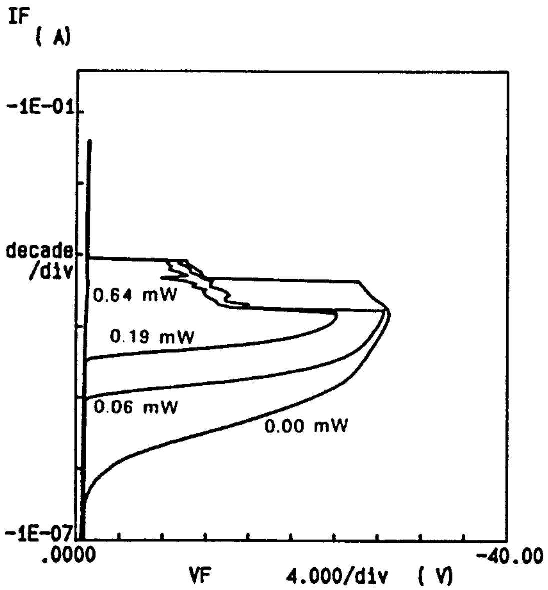

Fig. 4. Thyristor I-V curves for a 2.24 mm^2 device with indicated laser power directed into a 1250 μm diameter spot on the device.

The results of Figure 4 were typical of devices from the G0037 wafer (Table 1). The device was formed from a 2.24 mm^2 mesa (approximately square with 1.5 mm sides) and featured a dark breakover voltage of -29 volts at -173 μA. On subsequent current sweeps, the device was illuminated with the laser power levels shown. Note that device breakover voltages fell all the way to the forward-bias diode condition (Equation 4 above) with only 0.64 mW of light power (a power density of 0.29 mW/mm^2 in a 1250 μm diameter spot) at the 800 nm wavelength. These results indicate that our devices are extremely sensitive to illumination at this wavelength.

IV. RADIATION TESTS WITH AN X-RAY SOURCE

A. Febetron Tests

The three GaAs thyristor designs listed in Table 1 were tested for radiation tolerance using a Febetron 706 in the x-ray mode. The 600 keV electron source was aimed at a tantalum target to produce x-rays with a 3 nsec pulse width. Though the x-ray spectrum is not accurately known, the highest intensity is in the 100 to 300 keV range. Devices were placed within a shielded box in a closed screen room. They were exposed to x-ray pulses while connected to a voltage source set to a level below the dark breakover of the device. A series resistor, shunting electrolytic capacitor, and the current limit on the voltage source provided protection for the devices when they switched to the on state. Dose was adjusted by positioning the devices within the field of the source, and the x-ray output of the Febetron was monitored by passing the beam through a previously calibrated Radiation Sensing Field Effect Transistor (RADFET).

At each dose level, devices were tested at various bias voltages. Voltage was applied during each x-ray pulse and the switch state of the thyristor was recorded after the pulse. A map of the triggering levels was produced for each device.

Figure 5 shows results for wafer BE031; our 21 volt punch-through limited device having a mesa size of approximately 0.11 mm^2. The two curves represent light-voltage and dose rate-voltage combinations at which switching occurs for indicated light or dose rate levels. The shaded region on the right side of the graph shows voltage and dose rate combinations that have been found to induce switching in the device. The curve to the left indicates the switching or breakover voltage at a given laser power. Though optical power densities are not precisely known as they are in Figure 4, they are of the same order of magnitude.

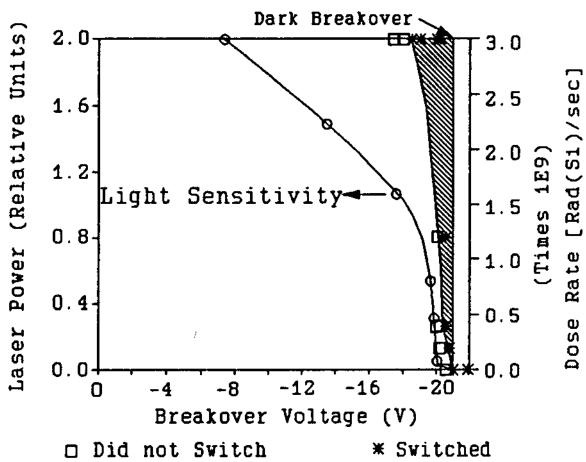

Fig. 5. Switching sensitivity of a punch-through-limited GaAs thyristor to light and flash x-rays. Breakover voltages are plotted against light in the curve on the left and against radiation in the hatched area on the right.

Note that at the levels of Figure 5, the device is triggered at significantly lower voltages by light than by x-rays. Thus, an operating bias voltage can be chosen at a level to the left of the hatched area. Note that at 20 V or 95 percent of the dark breakover voltage, the thyristor is insensitive to x-ray levels to 2 x 10^9 Rad(Si)/sec, yet it readily triggers on low light levels.

Similar results for the 18 volt avalanche-limited device (wafer G0004) appear in Figure 6. Here, the n^- blocking layer thickness is 2.5 μm, while the n^+ contact and p layers are 0.5 μm thick (see Table 1). Thus, we expect the device to be more sensitive to radiation than the BE031 device with its thinner layers; provided the transistor gains α_1 and α_2 have the same sensitivity to photocurrent for both device types. Note that the breakover voltage drops from a dark level of 18 volts to less than 15 volts at 2 x 10^9 Rad(Si)/sec (83 percent of the dark level.)

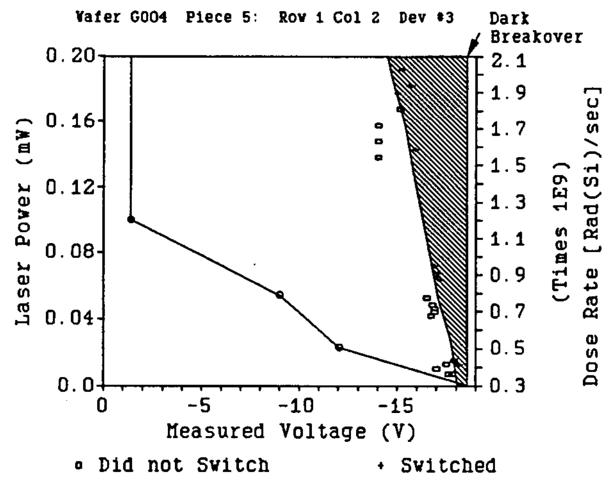

Fig. 6. Sensitivity of an avalanche-limited GaAs thyristor to light and to flash x-rays. Blocking layer thickness is 2.5 μm.

Radiation results for a device from the G0037 wafer appear in Figure 7. This device was designed for maximum breakover voltage with a blocking layer thickness at 2.5 μm, as indicated by Table 1. Its laser triggering characteristics appeared in Figure 4. Note in Figure 7 that the breakover voltage falls from a dark value of -29 volts to approximately -18 volts with 2 x 10^9 Rad(Si)/sec (60 percent of the dark value). Thus, even though the dark breakover is considerably higher than for the device in Figure 5, the design shows a much greater sensitivity to radiation effects.

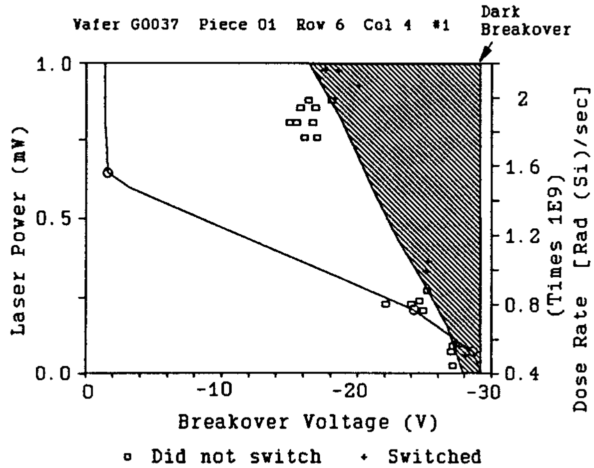

Fig. 7. Sensitivity of a GaAs thyristor to light and flash x-rays when avalanche and punch-through are balanced.

Other devices from the G0037 wafer showed similar levels of sensitivity to radiation. Because of the localized effects described above, dark breakover values varied widely; from -12 to -39 volts. At 2 x 10^9 Rad(Si)/sec, the devices exhibit breakover voltages between 40 and 90 percent of their dark values. Devices with high leakage currents and low dark breakover voltages were, in general, less sensitive to radiation, but would be of limited usefulness in actual applications.

B. Device Area and Radiation-Induced Photocurrent

The radiation-induced photocurrent was measured for several of the devices during tests with the Febetron. These curves were obtained from a Tektronix 7912 transient digitizer triggered by the Febetron source. As expected, peak external photocurrent was essentially proportional to device area. Changes in breakover voltage with dose rate, however, were not greatly influenced by device area. This was due to the fact that photocurrent densities in the device remained approximately constant, even though total device volume (and thus photocurrent) was increased. This is an important result with respect to device scaling, since radiation tolerance is maintained even for larger devices designed to switch greater peak currents.

Preliminary results from our transient measurements also indicate that the time delay associated with switching in these thyristors is affected by dose and applied voltage. While these results are not yet complete, they indicate that radiation pulse lengths may affect the response of our devices.

C. Neutron Effects

Thyristors from wafers BE031 and G0037 were also tested following exposure to neutrons. Neutron bombardment reduces carrier lifetime, and hence the gains of the linked transistors of the thyristor. This increases the breakover voltage to a level nearer that of punch-through or avalanche, and also tends to reduce the sensitivity of the device to triggering by laser light or radiation.

The BE031 devices were tested for basic function after exposure at the Sandia National Laboratories Annular Core Research Reactor. At 10^{14} n/cm^2, the devices could be triggered by an 800 nm laser operating in the tens of mW. At 10^{15} n/cm^2, however, the devices could not be triggered by 800 nm laser light up to our equipment limit at several hundred mW.

Devices from wafer G0037 were also bombarded with neutrons. These devices were first characterized in the laser and radiation-dose-rate tests as in Figures 4 and 7. They were then exposed to 10^{13} and 10^{14} n/cm^2. In Figure 8, we see the post-neutron laser test results for the device of Figure 4. Note that the magnitude of the dark breakover voltage has been raised from -29 to -35 volts and that the laser power required for full reduction of the breakover has gone from 0.65 to 3.0 mW (with a 1250 μm diameter laser spot on the device). Note in Figures 4 and 8, however, that the low-voltage photocurrents at the 0.06 and 0.2 mW light levels are almost equivalent before and after neutron exposure. This result indicates that the transistor gains are reduced by neutron bombardment, even though the quantum efficiency of the device has not changed at this neutron fluence. A lack of change in quantum efficiency is well documented for GaAs photodetectors up to 10^{13} n/cm^2.[2]

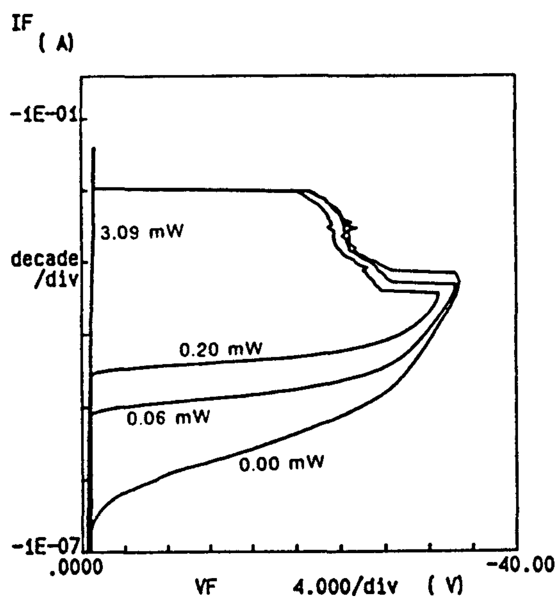

Fig. 8. I-V curves for the thyristor of Figure 4 after neutron bombardment to 10^{13} n/cm^2.

The neutron-bombarded devices were tested for radiation tolerance in the Febetron test facility. Results for the G0037 device of Figures 4, 7, and 8 appear in Figure 9. The tolerance to ionizing radiation was raised, accompanied by an increase in laser power required for switching (as documented in Figures 4 and 8). Note that the breakover voltage at 2 x 10^9 Rad(Si)/sec has changed from -18 volts in Figure 7 (60 percent of dark breakover) to -28 volts in Figure 9 (80 percent of dark breakover). This reduced sensitivity to ionizing radiation results from reduced gains in the linked transistors for this device. Other neutron-bombarded devices showed much larger reductions in their sensitivity to triggering by radiation. These wide variations are currently under investigation.

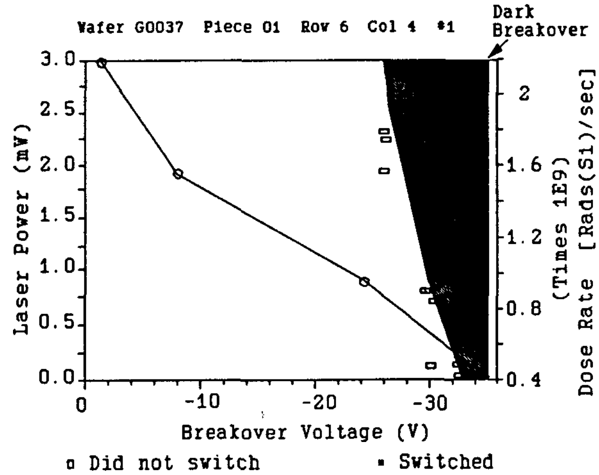

Fig. 9. Sensitivity of a GaAs thyristor to light and flash x-rays after neutron bombardment to 10^{13} n/cm^2.

At 10^{14} n/cm^2, radiation tolerance and required laser power were increased dramatically. With this neutron fluence however, device performance sometimes became unstable. Current paths in the devices tended to be confined to filaments, causing breakover voltages to drop as the devices were repeatedly switched.

VII. CONCLUSIONS

Radiation-hardened, light-activated thyristor switches have been demonstrated using GaAs. Devices were observed to trigger on a few tenths milliwatt/mm^2 of 800nm light power density and exhibit immunity to flash x-ray rates of 2 x 10^9 Rad(Si)/sec. Intrinsic GaAs properties of high optical absorption coefficients and low carrier diffusion lengths allow designs that discriminate between low light levels for triggering and high dose rates of x-rays. Breakover voltages in excess of 30 V were reported and devices currently under study exhibit breakover levels between 50 and 60 V. The thyristors show some decrease in optical and x-ray sensitivity upon neutron exposure in excess of 10^{13} n/cm^2. At 10^{14} n/cm^2, there were major reductions in photon sensitivity, and some instability was observed in these early designs.

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References

[1] J. E. Schroeder, A. Ochoa, and P. V. Dressendorfer, "Latch-Up Elimination in Bulk CMOS LSI Circuits," *IEEE Trans. on Nuclear Science*, vol. NS-27, pp.1735-1738, December, 1980.

[2] J. J. Wiczer, "Radiation-Hardened Optoelectronic Components: Detectors," *Proceedings of the SPIE*, vol 616 pp. 254-262, 1986.

[3] A. G. Kechek and V. V. Rossin, "Photon Mechanism of Propagation of a Turned-On State of a Gallium Arsenide Thyristor," *Sov. Phys. Semicond.*, vol. 18, pp 640-643, June 1984.

[4] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed., New York: John Wiley and Sons, 1981, p.76.

[5] S. M. Sze and G. Gibbons, "Avalanche Breakdown of Abrupt and Linearly Graded P-N Junctions in Ge, Si, GaAs, and GaP," *Appl. Phy. Lett.*, vol 8, pp.641- 1967.

[6] W. W. Chow, "GaAs pnpn Thyristor Modelling," SAND89-1044, Albuquerque, NM: Sandia National Laboratories, (Publication pending as of June, 1989).

[7] A. Blicher, *Thyristor Physics*, New York: Springer-Verlag, 1976, pp26-27.