

DOPED CONTACTS FOR HIGH-LONGEVITY OPTICALLY ACTIVATED, HIGH GAIN GaAs PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES

A. Mar, G. M. Loubriel, F. J. Zutavern, M. W. O'Malley, W. D. Helgeson,
D. J. Brown, H. P. Hjalmanson, and A. G. Baca
Sandia National Laboratories, Albuquerque, New Mexico 87185-1153

R. L. Thornton, R. D. Donaldson,
Xerox Palo Alto Research Center, Palo Alto, California 94304

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ABSTRACT

The longevity of high gain GaAs photoconductive semiconductor switches (PCSS) has been extended to over 100 million pulses. This was achieved by improving the ohmic contacts through the incorporation of a doped layer that is very effective in the suppression of filament formation, alleviating current crowding. Damage-free operation is now possible with virtually infinite expected lifetime at much higher current levels than before. The inherent damage-free current capacity of the bulk GaAs itself depends on the thickness of the doped layers and is at least 100A for a dopant diffusion depth of 4 μ m. The contact metal has a different damage mechanism and the threshold for damage (~40A) is not further improved beyond a dopant diffusion depth of about 2 μ m. In a diffusion-doped contact switch, the switching performance is not degraded when contact metal erosion occurs, unlike a switch with conventional contacts. This paper will compare thermal diffusion and epitaxial growth as approaches to doping the contacts. These techniques will be contrasted in terms of the fabrication issues and device characteristics.

I. BACKGROUND

The subject device of this paper is the optically triggered, high-gain lateral GaAs photoconductive switch (PCSS). They are constructed using semi-insulating (SI) GaAs of high resistivity $>10^7 \Omega\text{-cm}$ and metal contacts that are used to connect the switch to an energy source and a load. At electric fields above 4 to 6 kV/cm these switches exhibit high gain.¹ In the "on" state the field across the switch stabilizes to a constant called the lock-on field. During high gain switching, the PCSS emit

bandgap radiation by carrier recombination. This radiation under high gain operation, when imaged, is in the form of filaments.²

Although such high-gain operation is useful for many applications, the filamentary nature of this current impacts negatively the operational lifetime of the switches. This is manifested in the form of damage of the semiconductor to metal interface that initially appears as a trench, metal erosion, or damage in the GaAs away from the contacts (in the gap between the contacts). Contact erosion is an important damage mechanism since it is the main cause of degradation of switching characteristics, resulting in higher on-state resistance and voltage drop, and ultimately the ceasing of switch function.

II. OPTICALLY-INDUCED DIFFUSE AND MULTIPLE FILAMENTS

Damage to the PCSS contacts occurs due to current crowding at the point of filament termination at the edge of the contact. This is exacerbated by the difficulty in making low-resistance ohmic contacts to SI GaAs. We have previously shown³ that the trigger light can be applied to diffuse the filaments near the contacts, improving the current distribution and longevity. Another refinement of this technique we have investigated is multiple filaments using multiple line triggering as shown in Figure 1.

In this example we have used trigger light imaged into 8 lines across the width of the switch to initiate 8 distinct filaments that the current will be distributed amongst. When triggered in this manner, switching at 400A results in current drop of only 2% after 100 shots. The same

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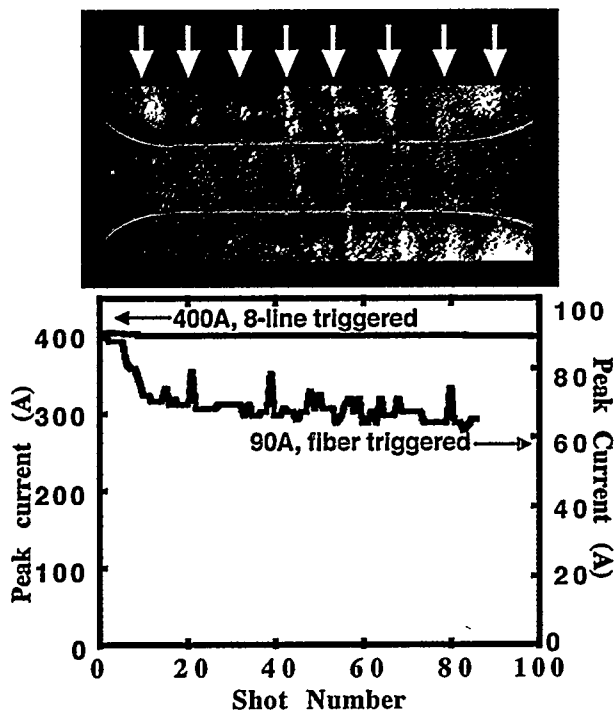


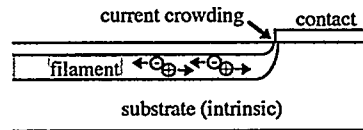
Figure 1. Switch lifetime improvement using multi-line vs. fiber spot triggering.

switch operating at only 90A shows a 28% current drop when fiber (spot) triggered.

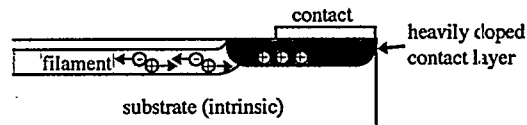
II. DOPED CONTACT FABRICATION

Due to the improvements in current distribution and lifetime demonstrated by the optical generation of carriers near the contacts, we have sought to incorporate doped layers with high carrier concentrations under the contact regions to reduce the contact resistance and spread the current, as shown in Figure 2. The doped regions also serve to transfer the point of filament termination from the metal - semiconductor interface to a doped semiconductor - semiconductor interface that is more robust against damage. Another embodiment of this idea under investigation involves the use of a thick, less conductive layer grown on top of the highly doped layer. This serves to strongly favor lateral current spreading as this vertical resistance serves to equalize the voltage drops among different current paths from the switch gap to different points on the metal contact. Such a "current leveling layer" has been demonstrated in vertical cavity semiconductor lasers to improve current injection uniformity in edge-injected structures.⁴ Two main approaches for the fabrication of switches with doped

Conventional switch:



Switch with doped contact layer:



Switch w/doped contact and resistive current-leveling layers:

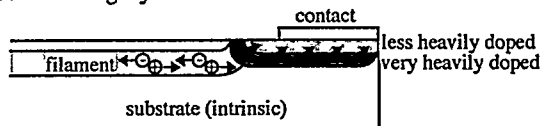


Figure 2. Current crowding and effect of doped contacts.

contact layers are being developed. The first is epitaxial growth using MOCVD to incorporate grown layers of highly doped material under the contacts. In one such approach, n-type (Si-doped) material is first deposited over the entire wafer and then etched away except in the regions where the switch cathodes are formed. This process is then repeated for a p-type growth (Zn-doped) for the anodes and then ohmic contacts are made to the doped material. Because this process results in a non-planar surface, another preferred approach under development utilizes patterned epitaxial regrowth. In this process, the contact regions are etched to some depth (a few microns) and highly doped GaAs is then regrown into these regions by the same thickness as the etch depth using a growth mask (SiO_2) that prevents growth elsewhere. This process is also repeated for the two different contact polarities and ohmic contacts made to the doped layers, which results in a planar structure. Because of non-idealities associated with the patterned regrowth, this process is still in development to overcome the issues of conductive material grown on the growth mask (into the switch gaps), and growth non-planarity.

The second technique we are pursuing for doped PCSS contacts is dopant diffusion. In this process, SiN_x is deposited and patterned to serve as a diffusion mask. An Si source layer and SiN_x encapsulation layer are then deposited and the Si driven in using a tube furnace at 800°C. These layers are left in place and patterned to serve as a diffusion mask for Zn. Vaporized Zn is

diffused into the substrate in an open tube furnace at approximately 600°C. Further details regarding the diffusion processing can be found in reference [5]. Ohmic contacts are then made to the doped regions to complete the fabrication. A microphotograph of such a completed device is shown in Figure 3.

III. PERFORMANCE OF PCSS WITH DOPED CONTACTS

The recombination radiation in PCSS filaments affords the ability to image them using an IR sensitive video camera. Such imagery of a filament in a PCSS with doped contacts is shown in Figure 4. The image shows that the doped layers are highly effective in the suppression of the filament formation near the contacts. This filament suppression at the contact is effective for peak current levels of up to, approximately 40-60A. In this regime, damage-free operation of the switch is obtained and lifetime is expected to be virtually infinite. In such a case at 80A, 2 million shots were fired with no detectable damage. At 23A, we obtained 100 million shots at which point the test was stopped, although the switch was still operating. Because high shot count longevity tests for such operation have become extremely tedious, our tests now typically are conducted to 100,000 shots. The switch is then characterized for the presence of any detectable damage under high magnification.

At sufficiently high currents, the filament is not sufficiently suppressed in the doped region to prevent damage to the contact. The nature of this damage and its effects however, is markedly different from that in a conventional PCSS. In the past, longevity tests have determined that damage due to current crowding in conventional PCSS contacts occurs first as a void or trench in the GaAs at the edge of the undoped contacts. Presumably due to the lower mobility of holes in GaAs, more severe damage occurs first at the p-contact of the PCSS. At higher currents and shot counts, this damage is accompanied by damage to the contact metal, in the form of erosion or loss of adhesion to the GaAs. These types of damage are shown in Figure 5. In the case of doped-layer contacts, this trend is reversed, where damage to the metal occurs at lower currents than it takes to damage the bulk material. In a conventional switch, this causes increased voltage drop and decreased current as the metal erosion occurs. This is not the case with PCSS with doped contacts, where the point of filament termination is on the doped region and the switching behavior remains

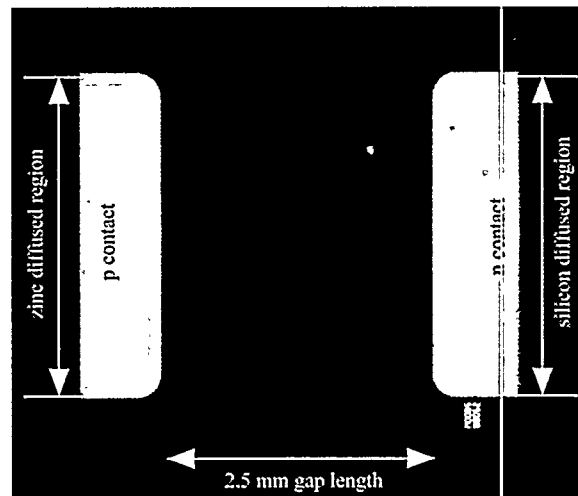


Figure 3. Microphotograph of completed PCSS with diffusion-doped contacts.

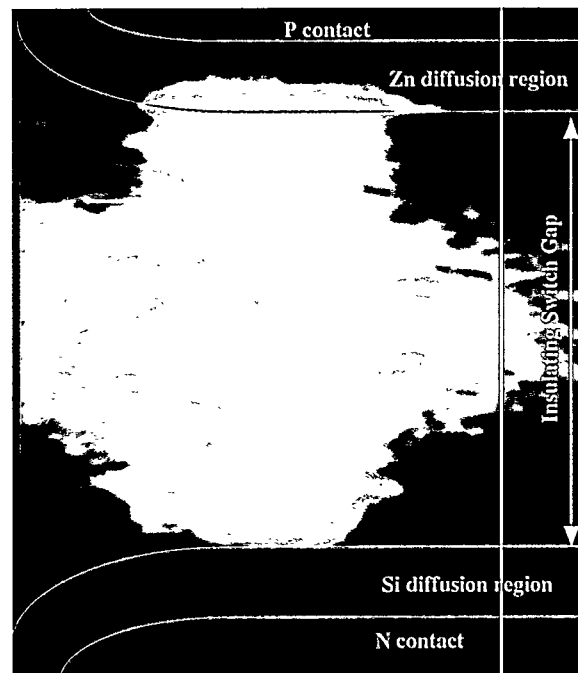


Figure 4. Filament suppression in the doped contact regions of a PCSS.

constant even if the metal contact is damaged, until the point where the external connection to the device is destroyed.

The level of current that can be switched without damage is dependent on the thickness of the doped layer beneath the contact. This was determined by preparing samples over a range of p-type anode diffusion depths (from ~1μm to ~4μm). The maximum current for operation with no detectable damage was then determined

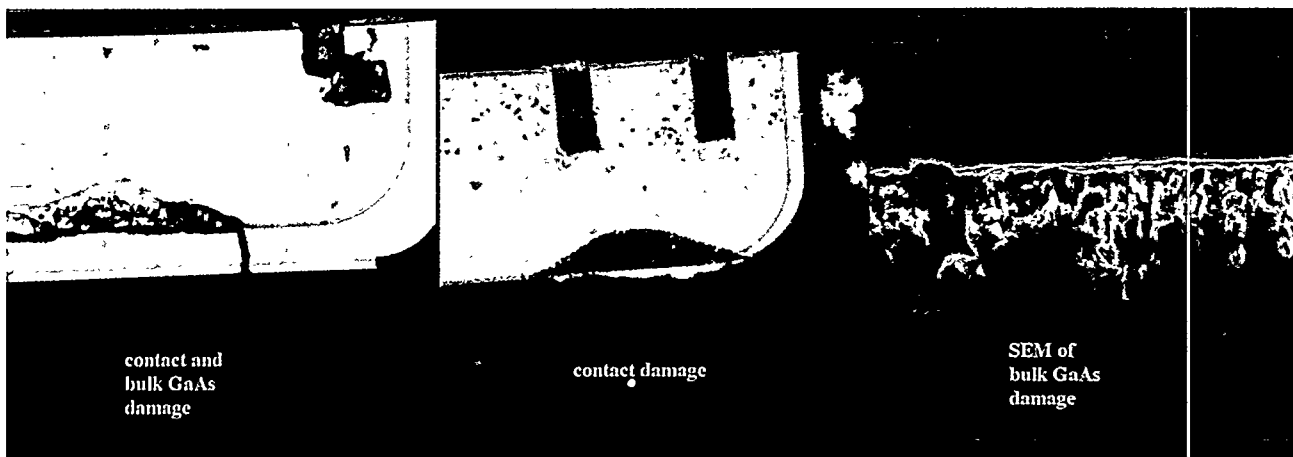


Figure 5. Different types of damage to PCSS contacts.

for the different diffusion depths. This was done accounting for two types of damage: damage confined to the contact metal (no switching current degradation), and damage to both the contact metal and bulk GaAs (switching current drops as damage accumulates). This characteristic is plotted in Figure 6. It is clearly seen that a thicker doped layer aids in suppressing damage to the bulk semiconductor. However, the improvement for damage to the contact metal tends to a limit of approximately 40A, with no further improvements with increasing diffusion depth. This implies a different mechanism for damage to the metal that is not adequately addressed by the current spreading in the doped contact layer. This indicates the requirement for a separately engineered solution for the fabrication of the contact metals, together with the doping in the semiconductor

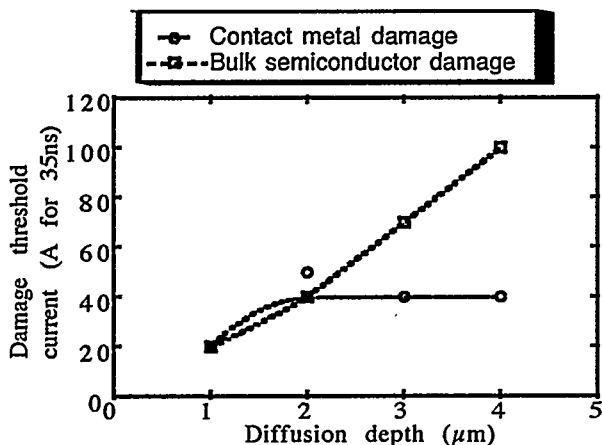


Figure 6. Effect of p-type dopant diffusion depth on maximum damage-free operating current.

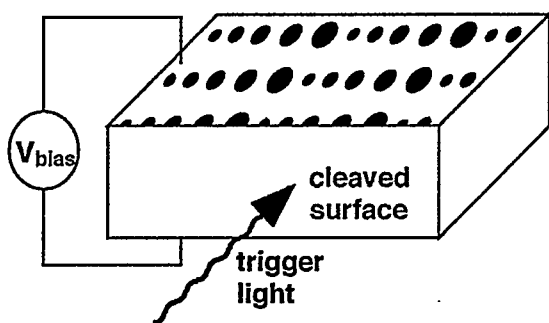
material, or the implementation of field shaping to enhance the lateral spreading of current at the contact. Beyond such an improvement, the data indicate the need for yet deeper diffusion depths to increase the inherent current capacity of the switch.

IV. LATERALLY-TRIGGERED VERTICAL SWITCH WITH DOPED CONTACTS

Non-coplanar switch geometries may offer some benefit for PCSS longevity. We are currently developing a vertical switch that also incorporates doped contact layers on both sides of the substrate. This eliminates the need for growth patterning or etching. A disadvantage of this approach has been the difficulty in injecting the trigger light into the middle of the switch gap. By using a cleaved surface for triggering, we are able to trigger this device the same manner as the co-planar switch, as shown in Figure 7. This allows us to retain the advantage of controlling the filament formation across the entire gap with the trigger light. Varying the size of the switch gap may be accomplished through the use of different wafer thicknesses or by stacking. This geometry combines the advantages of lateral switches with doped contacts of infinite effective depth orthogonal to the filament. The initial testing of this switch shows damage-free operation at currents of up to at least 50A.

V. APPLICATION TO FIRING SETS

For firing set applications we are interested in currents that range from 80 A to 3 kA and pulse durations that are as high as a few 100 ns with a requirement for lifetime of less than a few hundred shots. At the high current levels,



P- contact epitaxy: 2 μm thick p^+ GaAs

N- contact epitaxy: 2 μm thick n^+ GaAs

Figure 7. Laterally triggered vertical switch with top and bottom doped contacts.

the doped contact structure does not adequately suppress filament formation to prevent contact damage when a single spot trigger is used. One way to achieve increased longevity is to utilize multi-line triggering to spread the current into multiple filaments such that the current carried by a single filament is sufficiently low for the filament suppression in the doped material.

Fireset switches are generally neutron bombarded to enhance radiation hardness and high voltage holdoff. Another longevity issue for these switches is the long-term stability of the electrical properties of irradiated GaAs due to "self-annealing" of the neutron-induced damage. Figure 8 shows the time dependence of the DC voltage required to induce 50 μA leakage current in an irradiated PCSS. Although relatively preliminary, the data indicate that the enhanced DC holdoff will likely remain adequate for decades.

VI. SUMMARY AND FUTURE DIRECTIONS

The incorporation of a doped layer beneath PCSS contacts is shown to be very effective in the suppression of filament formation and alleviating current crowding to improve the longevity of PCSS. Damage-free operation is now possible at much higher current levels than before. We have now obtained over 100 million shots from a PCSS at 23A. At 80A, 2 million shots have been obtained with no detectable damage. The inherent current carrying capacity for no damage in the bulk GaAs depends on the thickness of the doped layers and is at least 100A for a dopant diffusion depth of 4 μm . Further independent improvement of the contact metal itself

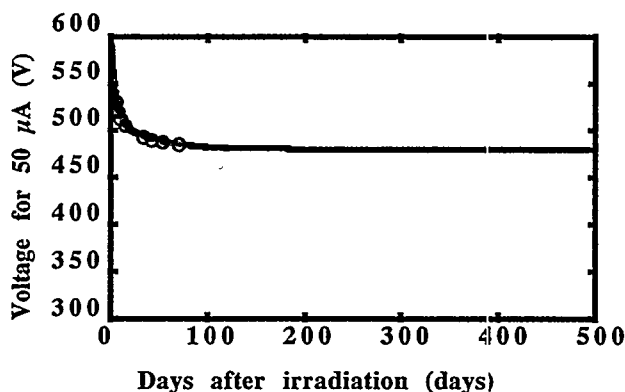


Figure 8. Projected time dependence of DC leakage current in a neutron-bombarded fireset PCSS.

and/or multiple filament triggering is necessary to obtain further overall improvements in longevity. However, in a doped contact switch, the switching performance is not degraded when contact metal erosion occurs.

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VII. REFERENCES

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