LONGEVITY IMPROVEMENT OF OPTICALLY ACTIVATED, HIGH GAIN GaAs PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES

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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 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 4μm. 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 2μm. In a diffusion-doped contact switch, the switching performance is not degraded at the onset of contact metal erosion, unlike a switch with conventional contacts. For fireset applications operating at 1kV/1kA levels and higher, doped contacts have not yet resulted in improved longevity. We employ multi-filament operation and InPb solder/Au ribbon wirebonding to demonstrate >100 shot lifetime at 1kV/1kA.

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 $>10^7$ Ω-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.

II. DOPED CONTACT FABRICATION

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 1.[3] 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 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_x) 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

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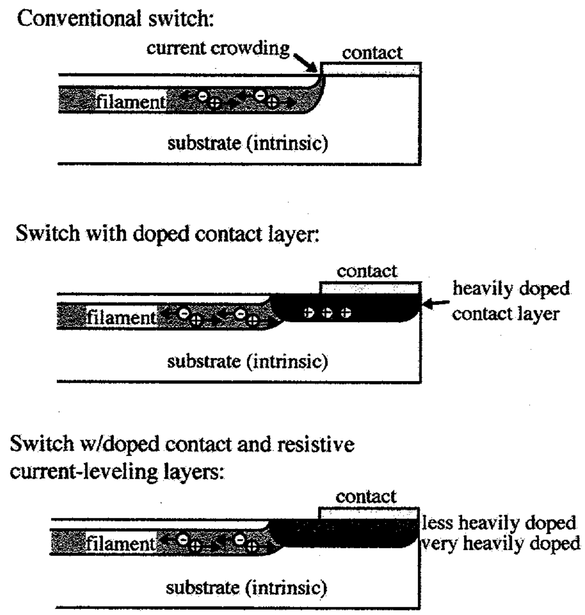

Figure 1. Current crowding and effect of doped contacts.

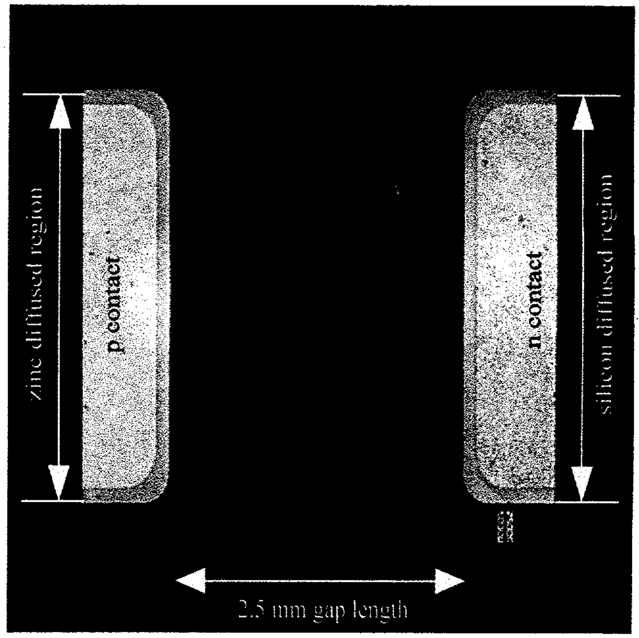

Figure 2. Microphotograph of completed PCSS with diffusion –doped contacts.

contacts are then made to the doped regions to complete the fabrication. A microphotograph of such a completed device is shown in Figure 2.

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 3. 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 inconventional 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 4. 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 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 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 5. 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

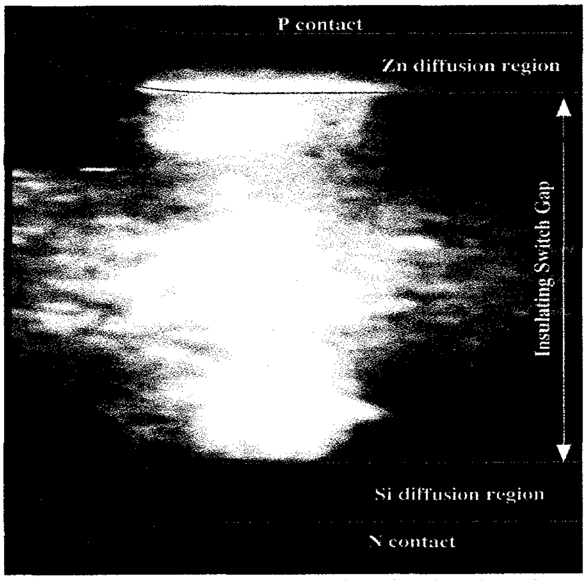

Figure 3. Filament suppression in the doped contact regions of a PCSS.

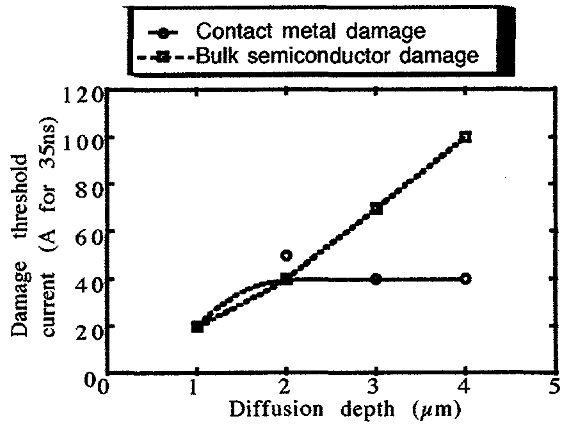

Figure 5. Effect of p-type dopant diffusion depth on maximum damage-free operating current.

engineered solution for the fabrication of the contact metals, together with the doping in the semiconductor 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. 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, the doped contact structure does not adequately suppress filament formation to prevent contact damage when a single spot trigger is used. We have previously shown that the trigger light can be applied to diffuse the filaments near the contacts, improving the current distribution and longevity. A refinement of this technique is the generation of multiple filaments using multi-line triggering. In this example, we have initiated 8 distinct filaments that the current will be distributed amongst. This is accomplished by precisely imaging the near-field of an 8-bar laser diode stack using an aspherical collimating lens together with a cylindrical lens. This anamorphic optical system precisely sets the magnification and aspect ratio such that the 8 laser lines exactly fill the gap length and width. When triggered in this manner, switching at nominally 400A results in current drop of only 2% after 100 shots, with continuing switch functionality, the result of which is shown in Figure 6. The same type of switch, operating at only 90A, shows a 28% drop after 86 shots when fiber (spot) triggered, at which point complete switch failure occurs.

We have also investigated the effects on longevity of various methods of bonding to the switch contacts. The switches incorporate a gold bondpad layer on the contact surface, which is leached into solution in molten conventional Pb/Sn solder. Thus, without a solder barrier layer in the contact, Pb/Sn soldering depletes the gold at

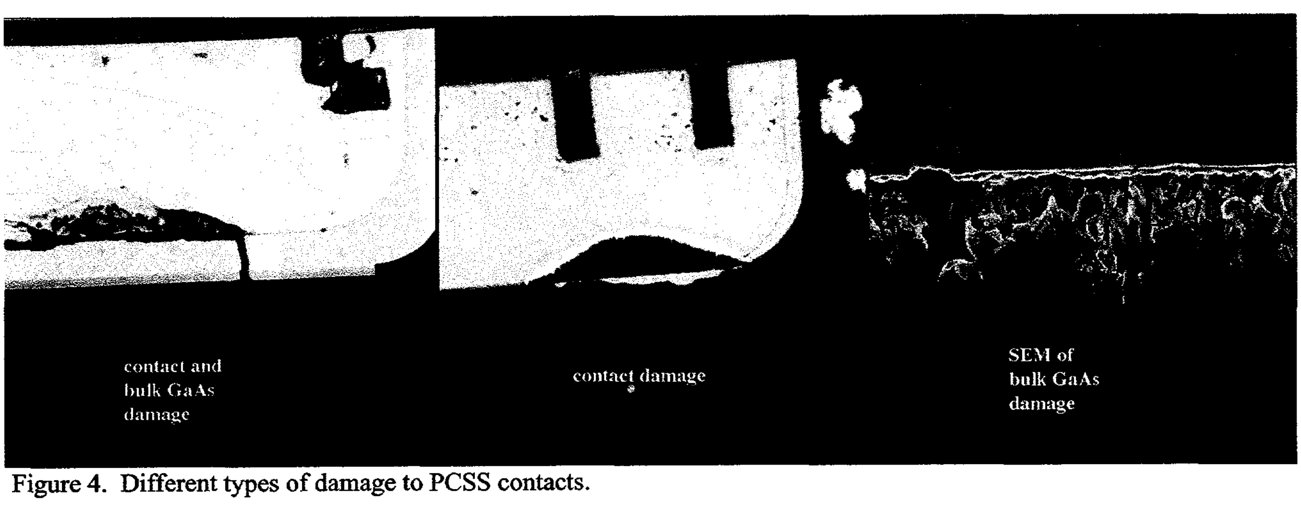

Figure 4. Different types of damage to PCSS contacts.

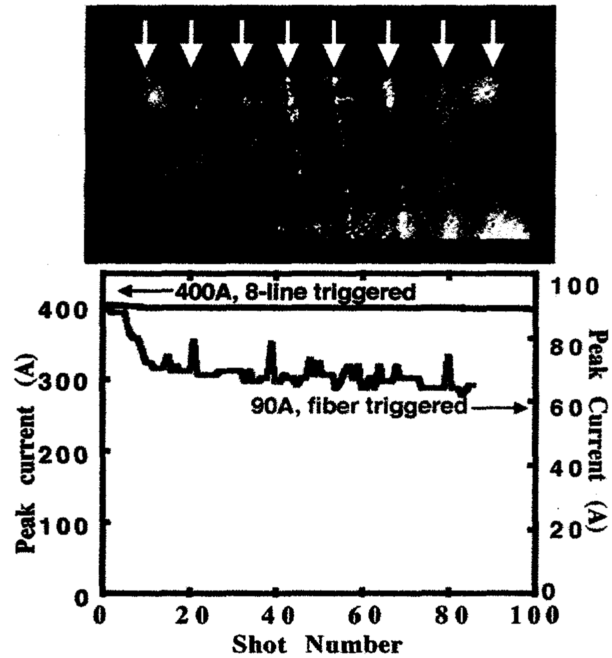

Figure 6. Multi-line triggering of PCSS for high current fireset applications.

the ohmic contact interface. We therefore implemented gold ribbon thermocompression wire (ribbon) bonding or Pb/In soldering to preserve the gold bondpad layer. We found that these techniques increased the longevity by about a factor of four.

By reducing the circuit inductance (~17 to <10nH), the initial peak current using a 0.3 mm gap switch rose to over 1300A. This allowed the use of reduced capacitance (50 vs. 90nF) to maintain 1kA peak. In this circuit, while *slightly* raising the charge voltage (from 1.0 to 1.1 kV), we achieved 120 shots at 1kA, as shown in Figure 7. At this point, the test was terminated to characterize the switch damage, but even more shots appear to be feasible. In another test, 2 switches connected in parallel also exceeded 120 shots at 1kA, using the 90nF capacitor.

Figure 8 summarizes the key developments leading to the achievement of >100 shot lifetime at 1kV/1kA. These

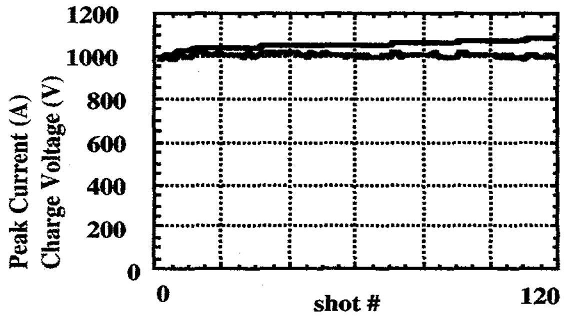

Figure 7. 120 shot test result at 1.0-1.1kV / 1kA.

techniques have been applied to testing at 3kV/3kA using 1mm gap switches, resulting in ~20 shot lifetime thus far.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

V. REFERENCES

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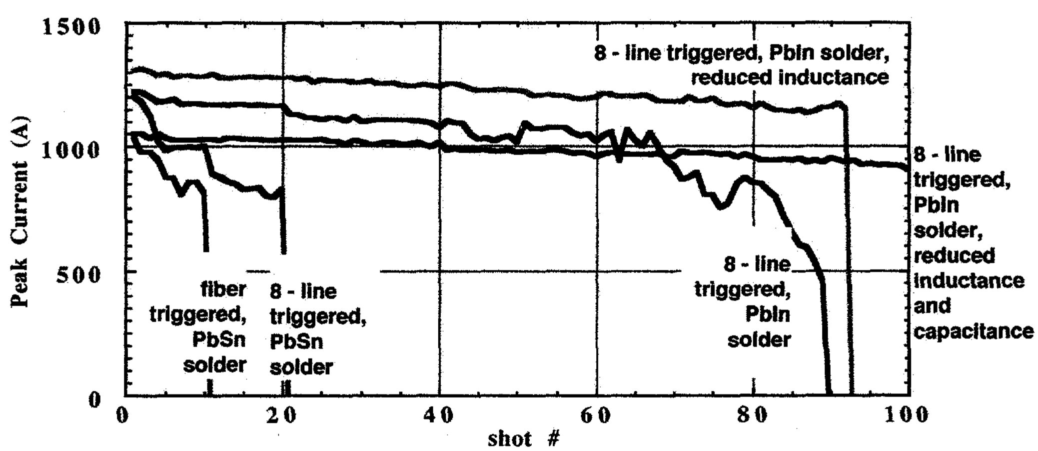

Figure 8. 1kV/1kA lifetime improvement due to multi-line triggering, In/Pb solder/wirebonding, & reduced inductance.