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LONGEVITY 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 well over 10 million pulses by reducing the density of carriers at the semiconductor to metal interface. This was achieved by reducing the density in the vertical and lateral directions. The first was achieved by varying the spatial distribution of the trigger light thereby widening the current filaments that are characteristic of the high gain switches. We reduced the carrier density in the vertical direction by using ion implantation. These results were obtained for currents of about 10 A, current duration of 3.5 ns, and switched voltage of ~2 kV. At currents of ~70 A, the switches last for 0.6 million pulses. In order to improve the performance at high currents new processes such as deep diffusion and epitaxial growth of contacts are being pursued. To guide this effort we measured a carrier density of 6×10^{18} electrons (or holes)/ cm^3 in filaments that carry a current of 5 A.

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1. Introduction

What is a PCSS: Our research has focused on optically triggered, high gain GaAs photoconductive semiconductor switches (PCSS) for pulsed power applications.[1] Table I shows the best results obtained with the switches. In this paper, we present results which demonstrate recent improvements in the longevity of GaAs switches.

Table I: Results of Tests with High Gain GaAs Switches

Table I Parameter	GaAs, high gain mode, best individual results.	GaAs, high gain mode, simultaneous results.
Switch Voltage (kV)	155	100
Switch Current (kA)	7.0	1.26
Peak Power (MW)	120	48
Rise time (ps)	430	430
Optical Trigger Energy (nJ)	2	180
Repetition Rate (kHz)	40,000	1
Device Lifetime (# pulses)	> 10,000,000	5×10^4, (at 77 kV)

Table I. The second column describes the best individual results for each parameter and are not simultaneous. The last column describes the result of a single experiment.

The GaAs switches used in this experiment are lateral switches made from undoped GaAs of high resistivity $>10^7$ Ω-cm and metallic lands that connect the switch to an energy source and a load. At electric fields above 4 to 6 kV/cm these switches exhibit high gain.[2,3] We have used trigger energies as low as 180 nJ to deliver 48 MW in a 30-50 Ω system.[4] 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, when imaged, is in the form of filaments.[5,6]

Applications of PCSS and Longevity Achievements and Requirements: The PCSS are being tested for use in: low impedance, high current firing sets in munitions; high impedance, low current electro-optic (Q-switch or Pockels

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cell) drivers for lasers; high voltage drivers for laser diode arrays; high voltage, high current, compact accelerators; and pulsers for ground penetrating radar (GPR). Each of these applications imposes a different set of requirements (see Table II) on switch properties which affect switch longevity. For example, GPR requires high voltage and high current with system longevity of well over 10 million pulses. Using a large (flashlamp pumped) laser a high gain PCSS (1.5 cm long) survived over 50,000 pulses while discharging a 77 kV transmission line resulting in a switch current of 625 A for 1.4 ns.[4] For firing sets we obtain 5 pulses at 1 kV, 750 to 550 A, 100 ns duration, with laser diode triggering. For electro- optic drivers we have demonstrated 0.65 million pulses (9 kV, 70 A, 3.5 ns).

Table II: Applications of PCSS

Application	Parameters (typical voltage, current, and other important constraints)	Required longevity	Demonstrated longevity
Firing sets	1 kV, 1 kA, compact size, low cost	100	1-5
Electro- optic drivers	3 kV to 6 kV, 100 A, long life, fast risetime	$>10^7$	10^6
Drivers for laser diode arrays	10 kV, 200 A, 5 ns pulse, compact size	10^3 to 10^8	10^5
Accelerators	100- 700 kV, series and parallel PCSS array	10^7	10^4
Ground penetrating radar	100 kV, 1 kA, 1 kHz repetition rate	10^7	10^4

Table II. Applications of PCSS including some of the relevant parameters of each application, the longevity required of the switch for each application, and the demonstrated longevity. The later results are not the demonstrated longevity at the parameters listed in the second column, but they are demonstrated at values that are similar to them.

Parameters that Affect Switch Longevity: As shown by the results just described, switch longevity is not related to a single parameter such as peak current, current duration, or total charge switched. There are three main factors that affect switch longevity: circuit properties, trigger properties, and switch properties. In order to study the effects of trigger parameters and switch parameters we test switches in a "longevity circuit." Section 2 of this paper describes this circuit and the nature of the damage to the switches. Examples of *circuit properties* are: initial switch voltage, peak current, duration of the switch current, charging pulse risetime, "recharge current," and repetition rate. Previous papers,[7,8] discussed the deleterious effects of increased peak current, large pulse width, and having a "recharge current:" a current that was much smaller than the peak current but lasted much longer causing a factor of 10 reduction in lifetime relative to the case when it is eliminated. Examples of *trigger properties* are: optical trigger energy used, optical pulse width, wavelength, spectral width, and spatial distribution of the trigger light. Section 3 of this paper will discuss the effect of using diffuse light to obtain a large increase in switch longevity. *Switch properties* are those that we can vary in switch fabrication: length and width of the active area, dark (prior to triggering) resistivity, contact configuration, contact polarity, coatings, and contacts to the GaAs. Sections 4, 5, and 6 of this paper will discuss contacts. Ion implantation and its beneficial effects on longevity are covered in section 4. In section 5 we present experiments that yield a value for the carrier density in a filament. These experiments guide the growth of contacts with diffused or epitaxially grown layers that are described in section 6.

2. Testing Circuit and Nature of Switch Damage

Since 1994, we have performed extensive switch longevity tests using a fixed circuit.[7] The circuit, shown in figure 1, has a pulsed power source that charges a 50 Ω coaxial cable to a few kV (up to 20 kV) in about 1 μs and the total pulse width is about 2 μs. A diode stack is placed between the power source and the coaxial cable such that, if the switch is triggered 2 μs after the start of the voltage pulse (as shown), the only remaining energy in the system resides in the coaxial line. This diode stack eliminates bleed through of current after the line is discharged (the "recharge current"). The duration of the current pulse is adjustable from 1 ns to 30 ns. For this study the current pulse duration was set at 3.5 ns. To trigger the switches we use laser diode arrays with a pulse duration of about 20 ns and a total energy of about 1 μJ. The light energy was delivered to the switch through a 300 μm diameter optical fiber. Various metallizations were tested to determine the damage mechanism and the best contact metallization. The best results obtained so far are with forward biased p-i-n switches and the following discussion is limited to that type of switch where the n contact is a made from Ge-Au-Ni-Au and the p contact is a Be-Au mixture.[9]

One can increase the longevity of a switch by using multiple fibers or by moving the fibers during the test. For example, by using multiple fibers, the current will be shared amongst various filaments. Also, by moving a single optical fiber along the whole width of the contact, one can avoid an area that is previously damaged and continue switching. Our methodology in this paper is to report on improvements in switch longevity with one (or two) fixed optical fiber (or fibers) to obtain a longevity for a fixed current per filament. For systems that may require more current multiple filaments may be triggered with multiple fibers.

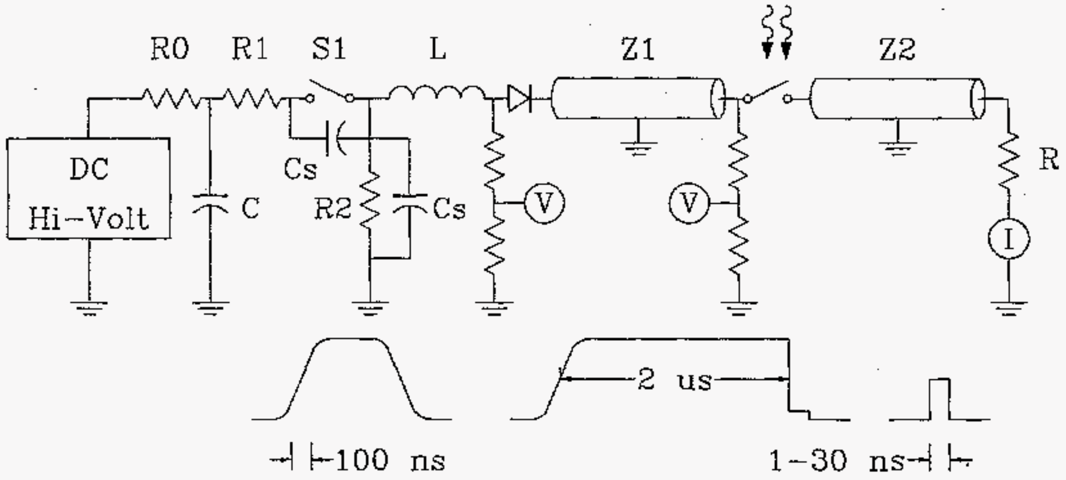

Figure 1: Circuit used for testing the longevity of high gain GaAs switches. With this circuit over 10,000,00 pulses have been obtained on a single switch with almost no damage.

The longevity tests have determined that, in most cases, the damage to the p contact is larger than that of the n contact. There are three types of damage to the switches: damage of the semiconductor to metal interface which initially appears as a trench, metal erosion, and damage in the GaAs away from the contacts (in the gap between the contacts). The trench damage (see figures 2 and 3) precedes all other damage and is visible with a scanning electron microscope (SEM) after a few hundred pulses. Figure 4 shows metal contact erosion and trench damage after 25,000 pulses and 100,000 pulses. Metal contact erosion is an important damage mechanism since it is the main cause of degradation of switching conditions and, ultimately, causes the switch to stop functioning. Gap damage is rare and, if it occurs, is normally after considerable contact erosion.

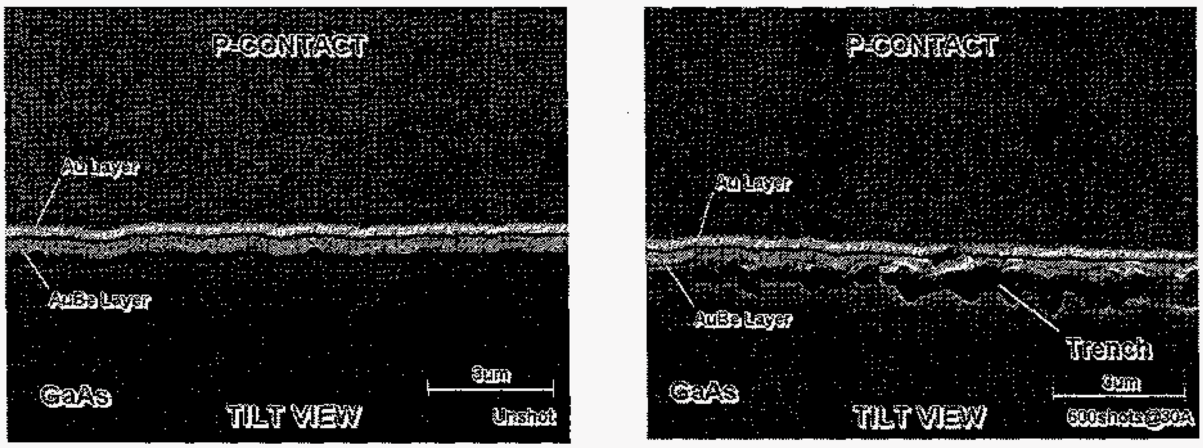

Figure 2: SEM pictures of a p-i-n switch prior to testing (left), and after 500 pulses at about 30 A (right). Note that the metal layer is not damaged even though there is a trench in the GaAs . The trench is about 1 μm in width and extends for 1.1 to 1.2 mm.

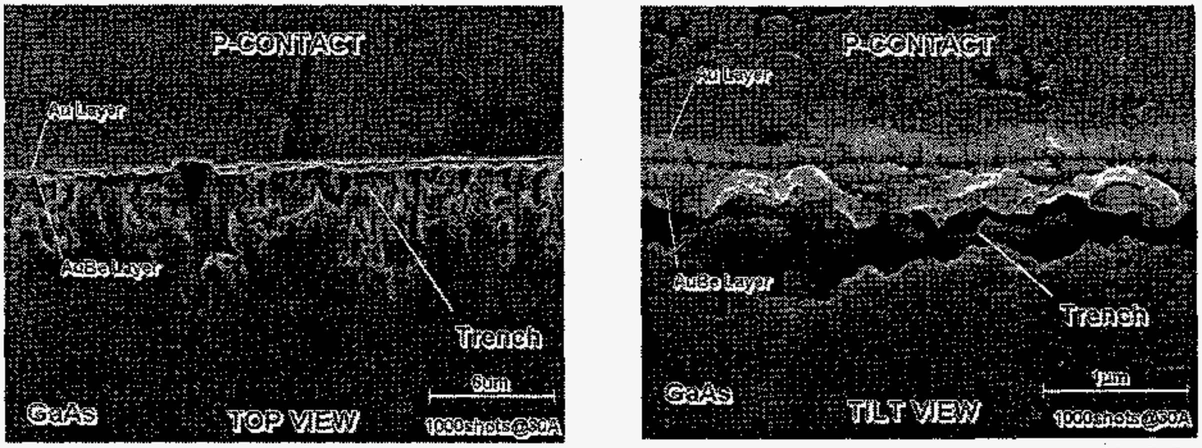

Figure 3: SEM pictures of an ion implanted p-i-n switch after 1000 pulses at about 30 A. The picture on the left is a top view, the one on the right shows a tilt view to emphasize the depth of the trench.

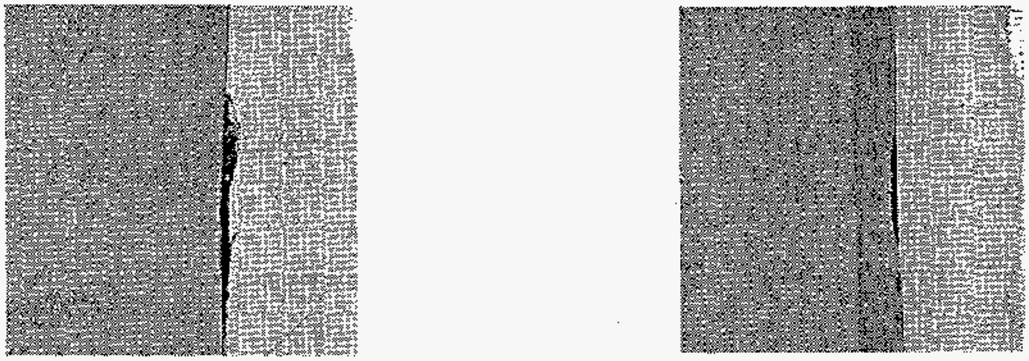

Figure 4. Pictures from an optical microscope. The field of view shows an area which is 0.7 mm wide by 1.2 mm high. Both switches imaged have active areas of 1.0 mm (in the horizontal direction) by 5 mm and were tested at 12 to 14 A (2.2 kV). The switch on the left is a standard p-i-n switch, the one on the right is a p-i-n switch with an ion implanted region (the shaded area) that starts 100 μm to the left of the p contact and extends under the whole area of the contact. The pictures were taken after 25,000 pulses (left) and 100,000 pulses (right) and in both cases the filament was not diffuse. The damage area in the standard switch is mostly due to contact damage with the top half of the damage being characteristic of contacts that have bad adhesion. The ion implanted switch shows trench damage with very limited metal contact erosion.

3. Spatial distribution of the trigger light: Diffuse filaments

In all the tests that we have described, the switch was triggered with a single laser diode array via an optical fiber whose output was aimed at the center of the switch. A typical filament that results from such a trigger light distribution is shown in figure 5 (left). Note that the filament is diffuse in the center of the switch. By moving the fiber to illuminate near one contact, we found out that the damage to the contact was reduced. Longevity was improved if the contact that was illuminated was the p contact. Our best longevity results have been obtained with two fibers placed as shown in figure 5 (right) in which case we have over 10,000,000 pulses with no damage. A picture of this switch after 10 million pulses is shown in figure 6. Since continued testing at 100 Hz is too time consuming, we are continuing tests at either higher currents with diffuse filaments or with focused filaments at these lower currents.

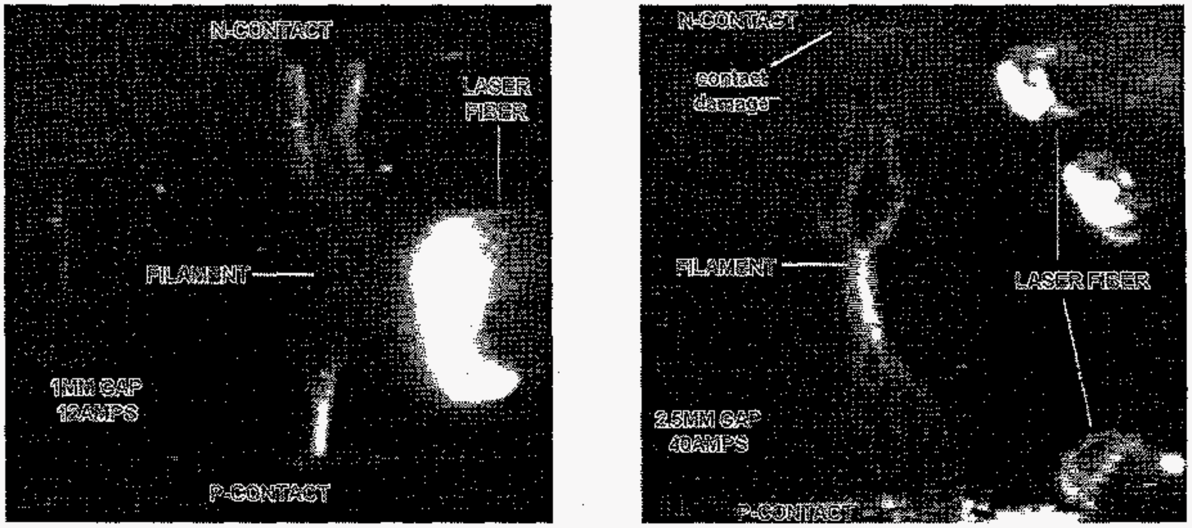

Figure 5. Pictures from an infrared sensitive camera showing the nature of current filaments in a high gain GaAs switch as a function of the spatial distribution of the light.

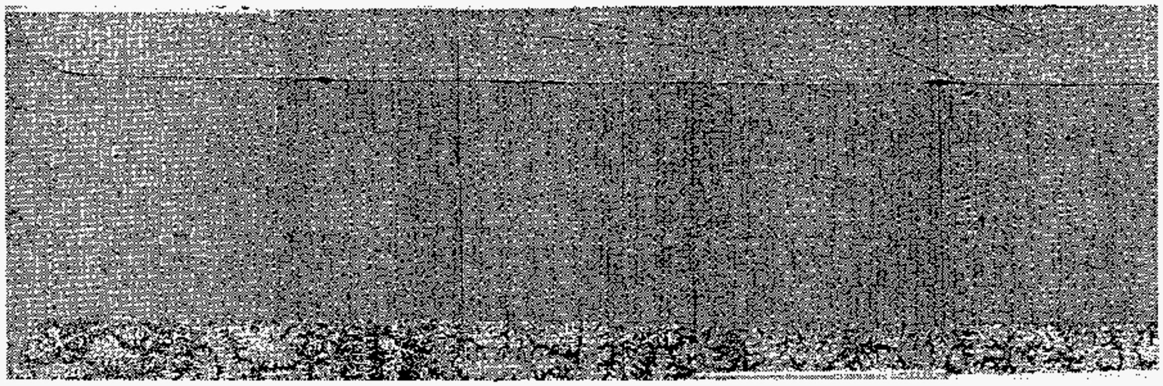

Figure 6. Picture from an optical microscope of a 1 mm (in the vertical direction) by 5 mm switch after 10 million pulses at 12 to 14 A (2.2 kV). The switch is a standard p-i-n switch which was triggered as shown in figure 5-right: two fibers to produce diffuse filaments at the p and n contacts. The only damage visible in the picture is in three separate regions of the p contact (the top one) but these occurred away from the place where the fibers were placed and probably resulted from earlier (without diffuse triggering) testing.

4. Contacts: Ion Implantation

Another way to reduce the carrier density in a filament as it crosses the semiconductor to metal interface is to dope the semiconductor directly underneath the contact and in a small area that extends into the gap (by 100 µm in our case). This doped area is visible in figure 4-right. We used Be ions (Be^+ and Be^{++}) as the dopants. Be^+ was accelerated at about 300 kV which results in a peak activated dopant concentration (of about 10^{19} carriers/ cc, in our case) at a penetration of 0.8 µm. The dopant concentration is smaller at all other depths. Be^{++} penetrates twice as deep as Be^+ but is not as heavily doped. As shown in figure 4 ion implantation results in a factor of about 8 reduction in damage and can shift the damage from the metal to the semiconductor. The ion implantation likely reduces current pinching at the semiconductor to metal interface and hence it reduces carrier density in the vertical (perpendicular to the surface) direction. An important question to ask is whether the reduction in damage is also due to the same effect as the diffused filament case (reduction in the density in the lateral direction). To determine this we have taken infrared sensitive pictures of the filaments in ion implanted switches. In most cases, the filament changes shape or intensity in the ion implanted region. While some images would lead to the conclusion that the filament enters the region and is diffused in it, others imply that the filament may go underneath the ion implanted region. One of these images is shown in figure 7.

5. Carrier density in a filament

A measurement of the carrier density in a filament is useful in developing new contacts since the dopant density should be larger than the carrier density in the filament. To obtain a rough value for the carrier density we used metal organic chemical vapor deposition (MOCVD) to grow epitaxial layers of AlAs followed by a GaAs layer (both 2 µm) thick on top of a GaAs wafer. Standard p-i-n contacts were deposited on top of the thin GaAs epitaxial layer. Since AlAs is an indirect bandgap semiconductor, we did not expect filaments in that material nor did we expect the filament to cross from the thin 2 µm thick GaAs layer to the thicker GaAs substrate. The grown layer turned out to be highly resistive: a switch with a gap of 400 µm had resistances of 4 GΩ in reverse bias and 700 MΩ forward biased at high voltages. This switch was then triggered and the filament images were compared to those of a standard switch. Figure 8 shows the images. The standard switch has filaments that are much thinner (6 µm thick), implying that the filaments in the 2 µm thick switch were confined to that layer and hence thicker (16 µm). The carrier density is then calculated from the known current and cross sectional area of the filament. For this calculation we need the electron and hole velocities. Since the microscopic electric field is not known, the carrier density was calculated for typical lock-on fields of 6 kV/cm, 8 kV/cm, and for 20 kV/cm where the velocities saturate. The carrier density was 5.8 x 10e18 per cc, 6.2 x 10e18 per cc, and 7.2 x 10e18 per cc (respectively, for the above fields). Thus a reasonable value of the filament's carrier density is 6 x 10^{18} carriers (electrons or holes) per cc.

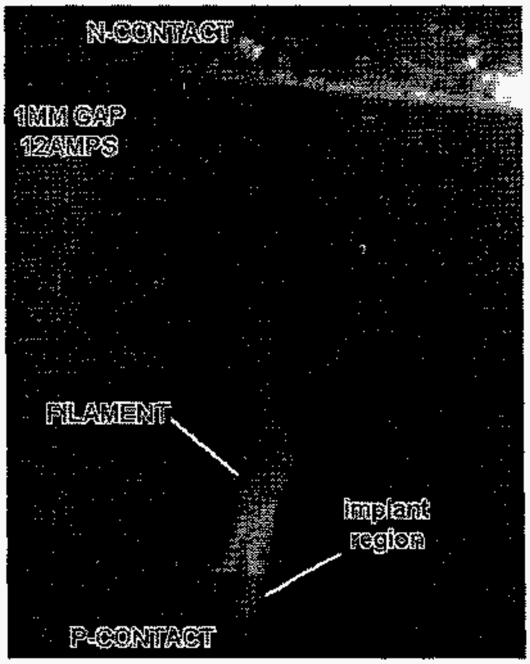

Figure 7. Picture from an infrared sensitive camera showing the nature of current filaments in a high gain GaAs switch as they enter the ion implanted region (at the bottom of the picture).

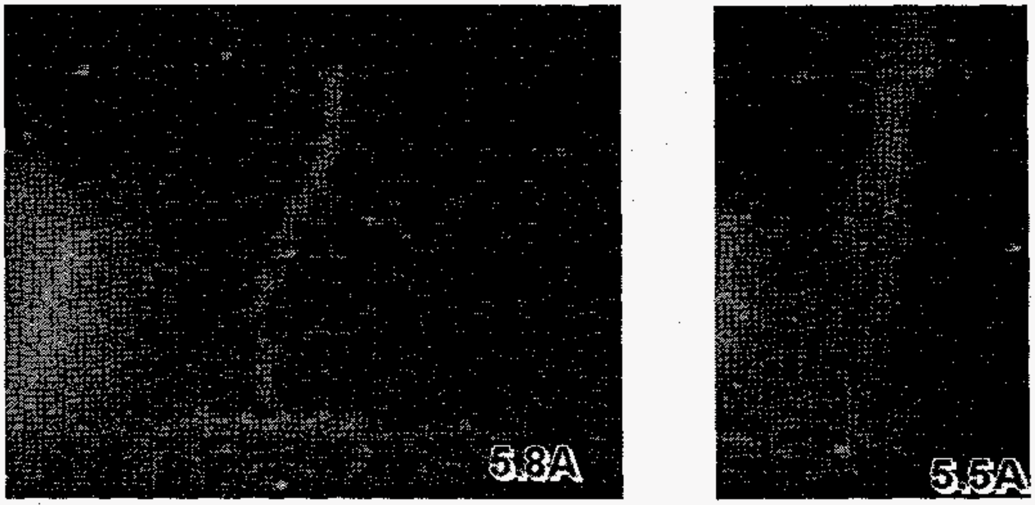

Figure 8. Filaments images of the current in a standard switch (600 μm thick, left) and a "2 μm thick" switch (right) at similar peak currents (5.8 A and 5.5 A, respectively). The filament's width is about 6 μm for the standard switch and 16 μm in the other. The cross sectional area of the filament in the left is unknown: 36 μm^2 if it has a square cross section, 28 μm^2 if it is cylindrical, and much smaller if its depth is tenths of microns. The area for the filament on the right is about 32 μm^2.

6. Future Work: Diffused and Epitaxial Contacts

There are three disadvantages of ion implantation: the bombardment causes damage to the crystal lattice, the implanted layer is relatively shallow when compared to the filament diameter, and the maximum implant is not at the surface. The first possibly makes the implanted GaAs more vulnerable to damage. The second does not result in optimal reduction of current pinching in the vertical direction. The third increases the contact resistance relative to the case where the peak dopant density is at the surface. These disadvantages motivate the pursuit of other new switch contact structures to improve device lifetime under high current operation. Three such ideas are schematically depicted in figure 9. One approach we are pursuing is deep diffusion. In this case, the acceptor species (zinc) is deposited over the areas where the p contacts are to be made, and exposed to elevated temperature. The zinc diffuses into the GaAs up to a depth of over 4 microns with peak dopant density at the surface of the material (gradually decreasing with depth). This thick dopant region beneath the p contacts will allow the current to spread, and will aid in the formation of low resistance metal contacts. Compared to implantation, this method offers the advantages of deeper penetration of the acceptor atoms, higher doping densities ($>10^{19}$ /cm^3), and minimal disruption of the crystal lattice in the doped areas.

Other structures under investigation rely on epitaxially grown contacts. Using growth methods such as MOCVD, a thick (~10 μm or more), highly doped (~5×10^{19} /cm^3) GaAs material is grown and patterned underneath the p contacts. This provides an even thicker layer for the current spreading to occur, and transfers the point of filament termination on the surface from a metal - semiconductor interface to a doped semiconductor - semiconductor interface, which should be more robust against damage. This may eliminate the trench damage we observe at the semiconductor- metal interface. Another embodiment of this idea under investigation involves the use of a thick resistive layer grown on top of the highly doped layer. This serves to strongly favor lateral current spreading as the vertical resistance of this layer now dominates the current paths from the gap to the metal contact. This vertical resistance serves to equalize the voltage drops among different current paths from the switch gap to different points on the metal contact. In the absence of this layer, the path of lowest resistance is simply the shortest distance path, resulting in current crowding at the part of the metal contact closest to the gap. This "current leveling layer" has been demonstrated in semiconductor lasers where it is used to eliminate hot spots in the laser output.[10]

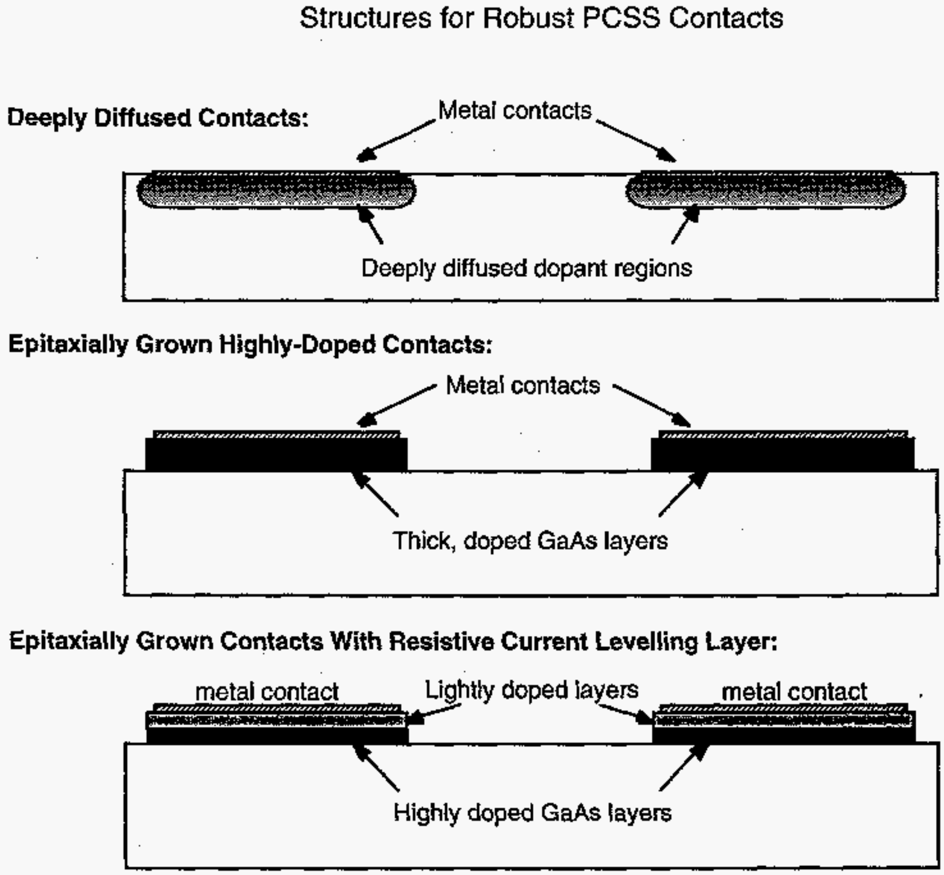

Figure 9. Structures for robust contacts.

7. Summary

Reducing the density of carriers in current filaments at the semiconductor to metal interface improves the longevity of high gain GaAs PCSS to well over 10 million pulses at about 10 A. This was achieved by changing the spatial distribution of the trigger source to illuminate near the contact and produce a diffuse filament. The longevity was also improved by using ion implantation. At currents of ~70 A, the switches last for 0.6 million pulses even with the reduced density afforded by the diffuse filaments. In order to improve their performance at these high currents, new processes such as deep diffusion and epitaxial growth of contacts are being pursued. To guide this effort we measured the carrier density in 5 A filaments: 6×10^{18} electrons (or holes)/ cm.^{3}

8. Acknowledgment

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