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CONTACT EFFECTS IN LIGHT

ACTIVATED GaAs SWITCHES

by

PETER S. DURKIN, B.S. in E.E.

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Chairman of the Committee

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CONTACT EFFECTS IN LIGHT ACTIVATED GALLIUM ARSENIDE SWITCHES

Peter Durkin

ABSTRACT

The purpose of this work was to examine the effects of various types of contacts on the switching behavior of a light-triggered power switch. The switch was constructed from a homogeneous wafer of chromium-doped gallium arsenide; the contacts were either ohmic, non-ohmic,or Schottky barriers. These were formed on the wafer in two geometries; both contacts on one side, and one contact on each side of the wafer. Various one-sided contact spacings were used to permit the effects of the location of the existing laser pulse to be studied.

A high voltage power supply (zero to 20 kV) was employed as the bias supply. A Nd:YAG laser, in the pulsed mode, was used to trigger the switch, which was mounted on a cold finger cooled to near liquid nitrogen temperature. Cooling reduced the dark current to manageable values (less than 1 μA), and also reduced the avalanche breakdown voltage. Measurements were made with a Tektronix Model 7834 storage oscilloscope; the amplifier input impedance was used as a 50 Ω load for the switch.

The results of the measurements indicate that ohmic contacts produced more reliable switching than the non-ohmic or Schottky contacts, inasmuch as the shape of the output current pulse was better, and the number of pulses which the switches could sustain

before the pulse shape deteriorated was greater, for the ohmic contacts. Surface discharge between the one-sided contacts obscured any differences in switching characteristics which might have depended on the location of the pulsed light excitation, so that no correlation between position and behavior could be obtained.

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CHAPTER I

INTRODUCTION

Laser pulses can be used to change the resistivity of high-resistivity bulk semiconductors, thereby generating high-power electrical pulses [1]. This phenomenon engendered many new applications for ultrafast optoelectronic switching that include AC power systems, pulse power systems [2], streak cameras, picosecond microwave generation and fast optical detection [1].

The change of resistance of a bulk semiconductor material with irradiation by a light source, that is, photoconductivity, is the result of the optical excitation of charge carriers. Photons create electron hole pairs, that are separated and swept out of the device by an applied electric field; therefore, the current in a circuit can be controlled by the photon flux [3]. Photoconductive events can be divided into two categories. The first is the result of directly photoinducing all the charge carriers with large amounts of incident laser light; in this case, photon energies are on the order of the bandgap of the semiconductor [4]. The second occurs when only a few charge carriers are optically generated; these cause a carrier avalanche in the high applied electric field [4]. If the resistance of the semiconductor is changed many orders of magnitude in a very short period of time, it is called a photoconductive switch, and will be efficient if its final resistance is much less than the external circuit resistance [3].

Conventional light sources can create carrier densities on the order of $10^{14}/cm^3$; however, a single picosecond laser pulse from a mode-locked solid-state laser can create a carrier density six orders of magnitude higher [2]. If the pulse is short enough it will deliver on the order of several hundred megawatts of peak power. This high peak power causes multiphoton excitation and the carrier density becomes a non-linear function of the laser intensity; therefore, a photoinduced plasma can be created in a semiconductor material with a bandgap energy larger than the energy of the absorbed radiation [2]. GaAs has a bandgap energy of 1.4 ev and can be excited by a laser with a photon energy of only 1.17 ev (1.06 μm).

Because the on-resistance of the switch is an important parameter in determining the switch efficiency, good ohmic contact, with small contact resistance, to bulk semiconductor material must be made. Irradiation from a laser pulse may reduce the resistance of the bulk material, but it will not, in general, affect the resistance of the contact; therefore, if the contact resistance is high, the efficiency of the switch will be low. However, Chi, et al. [2], have observed that the resistance of the contacts is not a problem at high DC bias, which suggests that the contact resistance may be caused by a barrier at the metal-semiconductor surface. One study of this problem has shown that ohmic contacts can be made on GaAs by alloying an Au-Ge eutectic film with a thin overplate of Ni [5]. There are, however, still questions respecting the effects of various types of contacts on photoconductive switches. The purpose of this work was to form several types of contacts, ohmic and non-ohmic, and determine their effects on the avalanche pulse, its shape and amplitude.

CHAPTER II

EXPERIMENTAL PROCEDURE

Sample Preparation

High Resistivity Bulk Material

Chrome-doped semi-insulating GaAs material was obtained from Morgan Semiconductor in wafers with an area 2.62 square inches and a thickness of approximately 0.016 inch; one side was polished. The orientation of the wafers was (110) $\pm$ 1/2°. The wafers were scribed into small rectangles, 5/8 inch by 1/2 inch, then mounted with ceresin wax on a three inch diameter circular aluminum disk, polished side down. The top surface was then mechanically polished on an orbital polisher (Coburn Model Rocket) using a 1.0 micron alumina polishing powder, followed by a 0.3 micron alumina powder, until a smooth surface was obtained.

The GaAs pieces were then removed and cleaned in trichlorethylene, acetone and methanol to remove the wax; they were etched in a 3:1:1 mixture of H_2SO_4:H_2O_2:H_2O for 30 seconds, and stored in isopropanol until required for use.

Contact Formation

Three types of contacts were examined in this work, ohmic, Schottky barriers, and non-ohmic. These were ar-

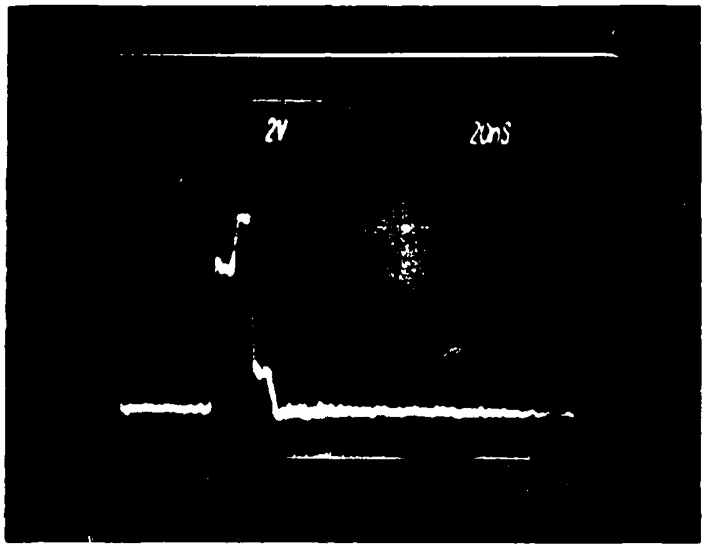
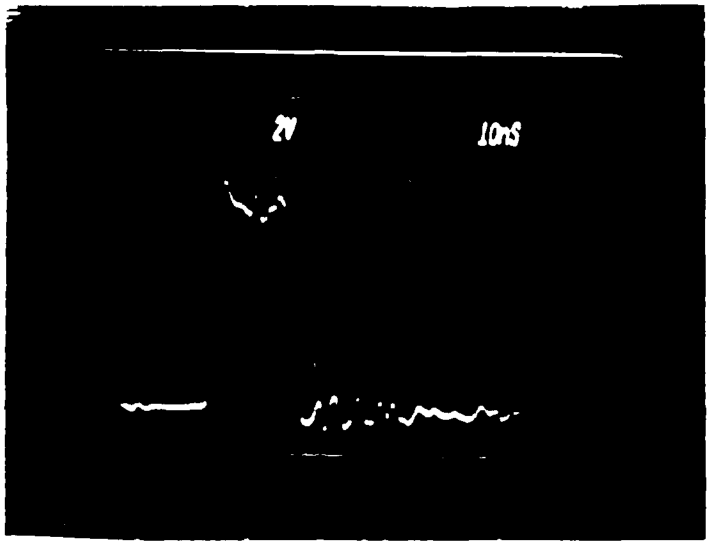
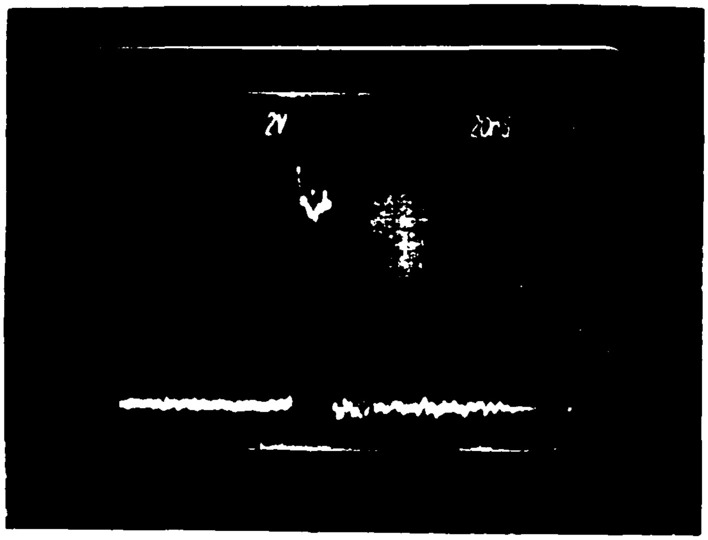


Figure 5. Distorted output pulse (71.6 kv/cm, × 100 attentuation) obtained with two-sided non-ohmic contacts for 782 nJ (relative).



(a)



(b)

Figure 4. Output pulse (66 kv/cm, × 100 attenuation) obtained with two-sided ohmic contacts for
a) 632 nJ (relative) and
b) 4300 nJ (relative).

Two-Sided Contacts

Ohmic Contacts

The bias voltage was set to 2.7 KV, corresponding to an electric field of 66 KV/cm. A self-sustaining, or avalanche, pulse occurred for a light energy as low as 632 nJ, with the energy meter. A 1000 V, 15 ns wide, output pulse was obtained, and, assuming that voltage division actually took place, the on-resistance of the sample was calculated to be 18 Ω. (This and subsequent resistance calculations assume a matched total load and delivery of one-half the charged line voltage to the combined switch and sampling load resistance. This is probably not a good assumption, inasmuch as the total load is not matched, but it provides a relative figure of merit for the effectiveness of the switch.) Figure 4 illustrates the avalanche pulses obtained with two different values of optical pulse energy.

Non-Ohmic Contacts

These samples were similarly biased at 2.7 KV, and the electric field was 71.6 KV/cm. A 1000 V, 17 ns, output pulse was obtained; the on resistance of the sample was calculated to be 18 Ω. In general, the results were similar for the ohmic and non-ohmic contacts; however, several of the output pulses for the latter were somewhat distorted (Figure 5). This distortion did not occur with the ohmic contacts.

CHAPTER III

RESULTS AND DISCUSSION

Current-Voltage Measurements

The DC current-voltage characteristics of the one-sided contacts were measured to determine to what degree their behavior was ohmic. It was not possible to make any meaningful dark measurements because of the very high series resistance of the semi-insulating material, so the region between the contacts was illuminated with a strong white light to attempt to reduce the series resistance of the material. The contacts themselves were shadowed by covering them with black electrical tape. The measurements were made by applying a bias across the contacts and measuring the resulting current flow; the voltage polarity was then reversed, and the current remeasured. No significant differences were found between the ohmic and non-ohmic contacts up to around 1500 V and 1 mA. The measurements were terminated here because of possible damage to the samples at higher powers. It is likely that the resistance of the intervening material was not successfully modulated, and that essentially only this resistance was being measured.

device and the laser pulse intensity were both high enough, the sample would conduct; discharging the charge line and producing a self-sustaining current pulse. The magnitude of this pulse was much greater than a normal photoconductive pulse. Its width depended on the length of the charge line between the sample and the 100 MΩ charging resistor. The output pulse length was kept approximately constant during the measurements. The magnitude of the voltage pulse appearing across the 50 Ω load was determined by the voltage division established by the load, the characteristic impedance of the line, and the on-resistance of the irradiated sample.

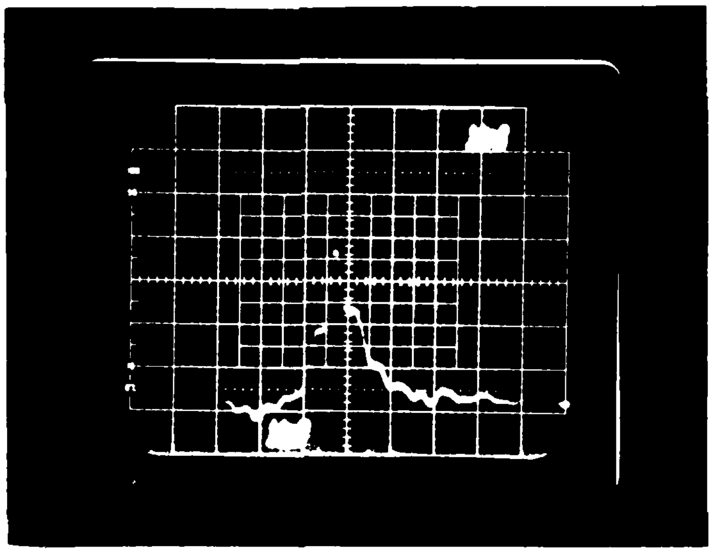


Figure 3. Laser output pulse.

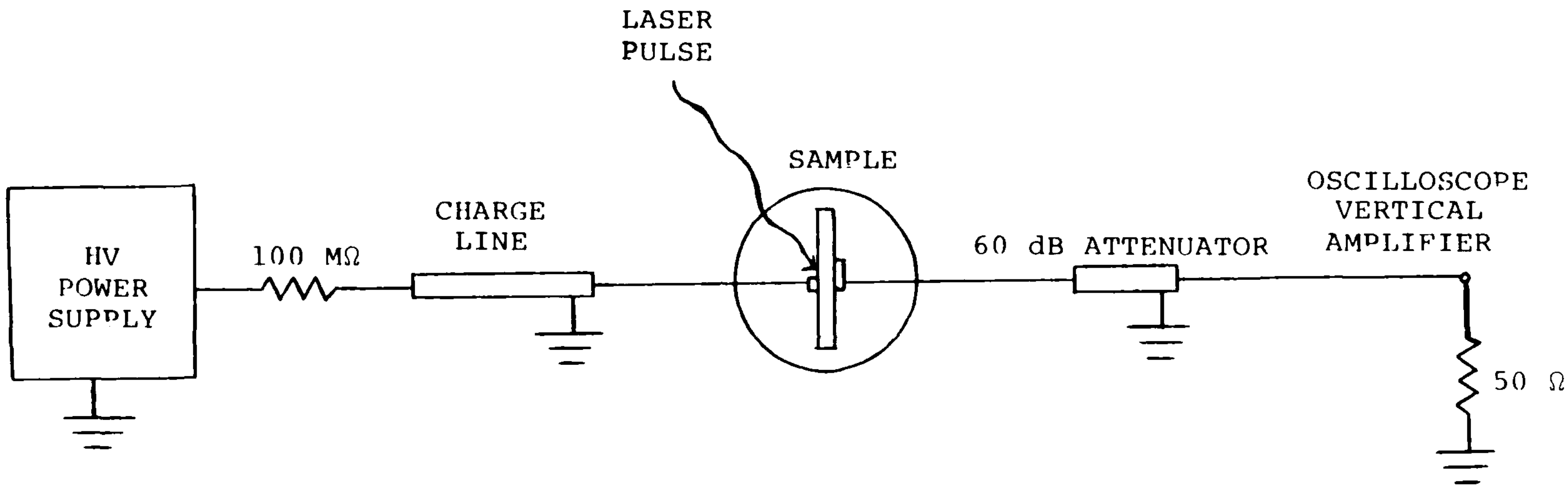


Figure 2. Experimental arrangement.

removed. The straight portion of the cold finger was placed in a vacuum flask filled with liquid nitrogen and allowed to cool for at least one hour.

Electrical and Optical Measurements

A six foot length of RG-58/V coaxial cable was connected as a charge line to one of the high voltage connectors on the cold finger. The other end of the cable was then connected to a variable high voltage DC supply through a 100 MΩ charging resistor. The second high voltage connector on the cold finger was tied through a 60 db wideband attenuator to a Tektronix model 7834 storage oscilloscope which provided a 50 Ω load to ground; this was used as a sampling resistance to obtain the output current pulse (Figure 2).

After the sample had been cooled down and biased to the desired voltage, it was optically pulsed with 1.06 μm radiation obtained from a Nd:YAG laser. The light pulse was focused down to a spot approximately 0.040 inch in diameter, using a lens with a focal length of 8.8 inches. The laser pulse was approximately 9 ns in duration, and the intensity could be varied by using different light filters. Figure 3 illustrates the light pulse, obtained from the photoconductive response of the sample. The intensity of the laser pulse was measured using an energy meter, but this provided only relative values. If the electric field across the finger and provided a mounting surface for the samples. However, electrical isolation of the sample was required so a sapphire insulator was introduced between the sample and the copper, permitting electrical isolation but good thermal contact. Two sapphire insulators were used. The first, used with the samples having two-sided contacts, was a disc 0.059 inch thick and 0.197 inch in diameter; it contained a concentric hole 0.039 inch in diameter which was not used in mounting the sample. The sample was held tight against the sapphire, which in turn was forced against the copper, by a Teflon® flap which overlapped the sample and which was bolted to the copper with a Teflon® screw. The surface of the sapphire resting against the copper was lightly greased with a copper filled grease (Crycon) to improve thermal contact. The second insulator was used for mounting the samples with one-sided contacts. This insulator was 0.5 inch in diameter and 0.079 inch thick; the mechanical mounting arrangement was found to be superior to the first, inasmuch as better thermal contact was made, and arcing to the copper was suppressed.

When a sample had been mounted onto the sapphire and copper sheet, the wires connected to the contacts were soldered to the high voltage connectors. The valve was then connected to a diffusion pump and the cold finger sample chamber was evacuated to better than 10^{-3} Torr; electric field ionizable gases and condensable vapors were thereby

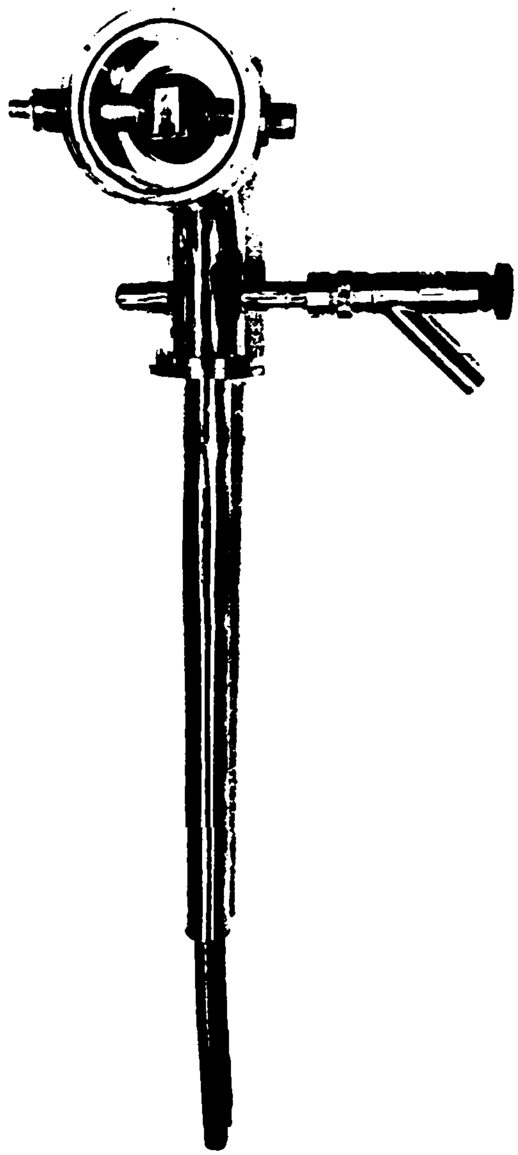


Figure 1. Cold finger.

temperature (77 K). A vacuum cold finger, with high voltage electrical feedthroughs was used for this purpose. The cold finger was made from a solid copper rod, 0.74 inch in diameter, and 30.5 inches long; the upper eight inches of the copper rod was bent into the form of a J. A 1.25 inches diameter stainless steel tube was welded to the copper rod 6.75 inches from the bottom of the straight section. The weld was such that a straight cylindrical cup concentric with the rod was formed; the length of the cup was 15.75 inches. The top of the cup was flanged, and a second stainless steel tube, two inches in diameter, was also flanged and bolted to the lower cup. A vacuum valve was attached to the upper tube just above the flange. The upper tube followed the shape of the copper rod and enclosed it concentrically. The bent end of the upper tube was also flanged, and bolted to a stainless steel ring, 1.75 inches thick, with a 3 inch inner diameter and a 4 inch outer diameter. The ring was grooved, and an O-ring was inserted. A circular quartz window, 4 inches in diameter and 0.75 inch thick, was set on the O-ring and held in place by way of a vacuum. The window provided optical access for the laser light pulse. Figure 1 illustrates the cold finger.

A flat sheet of copper, 0.127 inch thick, was bent into a U-shape, providing a more-or-less flat surface with area around 0.75 inch square; the sides of the U were 0.25 inch apart. This was welded to the top of the copper rod inside

Contact Geometry

Two contact geometries were employed in the measurements. In the first, two circular contacts, 0.040 inch and 0.020 inch in diameter, were placed opposite each other on opposite surfaces of the sample. Alignment was not concentric; the small circle was offset so that one point on its circumference lay directly above a point on the circumference of the larger circle. This arrangement permitted illumination and carrier generation near the contacts but not directly contiguous to the contacts. The second geometry consisted of two circles of equal diameter (0.040 inch) on the same surface, with their centers separated by 0.2 inch. This configuration permitted illumination and carrier generation near either contact or between them. In this manner, it was possible to examine the effects of illumination in relationship to contact type and polarity.

Two ohmic or two non-ohmic contacts were used in the overlapping contact system to provide two experimental configurations. In the second arrangement, four configurations were established: two ohmic contacts, two non-ohmic contacts, two Schottky barriers, and one ohmic and one non-ohmic contact.

Sample Mounting

In order to reduce dark current and thermal dissipations, the samples required cooling to near liquid nitrogen

500 °C for 4 minutes in a nitrogen atmosphere. The rectangular substrates were then scribed into individual samples, each sample with the desired number of contacts.

Schottky Barriers

Schottky barriers were formed exactly the same way as the ohmic contacts, except that no alloying was performed.

Non-Ohmic Contacts

Non-ohmic contacts were obtained by placing a small amount of silver bearing epoxy adhesive (Epoxy Technology EPO-TEK H31) directly onto the gallium arsenide and curing it in air at 150 °C for 30 minutes. The manufacturer's value for the resistivity of the cured adhesive is between 0.0001 and 0.00005 ohm-cm, so that any voltage drops during switching should occur at the interface between the adhesive and the gallium arsenide, and not in the adhesive itself. Electrical connection was made by inserting a thin wire, around 0.004 inch in diameter, into the adhesive before it was cured. This method was also used to make connection to the gold contacts; that is, a small amount of the epoxy adhesive was placed onto the gold contact, the wire was inserted, and the adhesive was cured. Interface resistance between the gold and the adhesive is expected to be negligible.

ranged in various configurations, but each type of contact was made the same way.

Ohmic Contacts

Ohmic contacts were formed by evaporating a gold germanium eutectic composition (88 Au/12 Ge). Evaporation was performed in a Varian model 3117 system using as a charge discs 0.034 inch in diameter by 0.015 inch thick; these were obtained from Cominco Electronic Materials with a typical purity of 99.995%. Approximately one hundred discs were loaded into an aluminum oxide coated tungsten boat (Mathis Type 53SB-AO-W), and evaporated onto gallium arsenide substrates which had been removed from the isopropanal and blown dry in nitrogen gas. The substrates were placed over metal masks which sat in grooved openings in a stainless steel fixture; evaporation was performed up through the masks. The fixture was located 1.2 inches above the evaporator boat. When the substrates and masks were in place, the evaporator was pumped down to around 3×10^{-7} Torr with liquid nitrogen in the cold trap, and evaporation was begun. A baffle was placed in front of the substrates and masks initially to prevent deposition of impurities; this was removed later during the evaporation. The process was repeated if contacts were desired on the other sides of the chips. After deposition, the contacts were alloyed in electric furnace (Heavy Duty Electric, Type M-2012-S) at

One-Sided Contacts

The one-sided contact configuration was used to examine the effects of the location of the optical excitation relative to the contacts. The light spot was centered between the two contacts and the intensity of the pulse was increased until avalanche photoconduction occurred. The bias voltage required for avalanche photoconduction for the one-sided contacts was 12 KV, corresponding to an electric field of 30 KV per cm. This was the highest practical electric field which could be used without excess dark current flow and surface breakdown. (The connecting cable was changed to RG-9 here, to withstand the higher voltage.) Finally, the spot was moved adjacent to the second contact and the procedure was repeated. The polarity of the voltage across the contacts was reversed and measurements were performed again. The light spot was then relocated in the center between the contacts, and the device was pulsed repetitively, with a three second period, to determine the total number of avalanche pulses which could be produced by the device without deterioration of the pulse shape. The magnitude of the switched out pulse for all the contacts varied from pulse to pulse, being as low as 2000 V and as high as 3200 V. The pulse width in all cases was approximately 3 ns and was rounded at the top instead of being flat, as it was for the two-sided contacts. Figure 6 shows

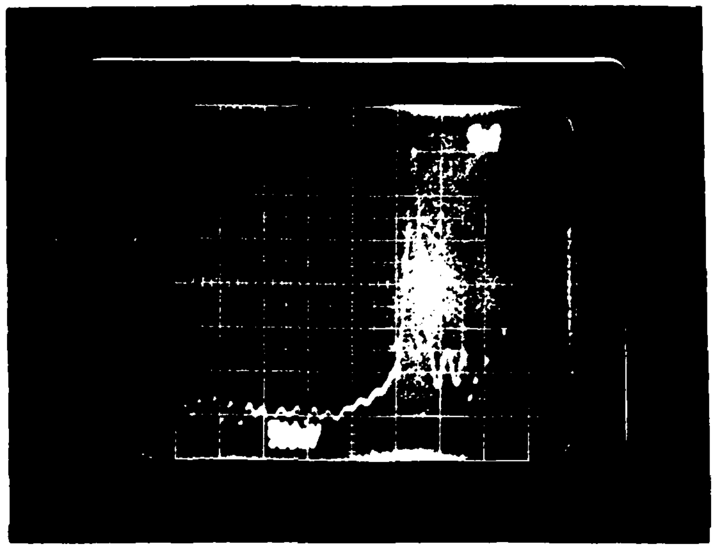


Figure 6. Output pulse (30 kv/cm) for a one-sided sample with ohmic contacts for 6.5 μJ.

a typical output pulse; in this case, the contacts were ohmic. The resistance of the GaAs device under illumination was calculated to be around 48 Ω.

Tables 1 through 4 contain the minimum relative energies required for avalanche photoconductivity for all the samples. Right contact, left contact and centered measurements were made for one polarity, then the polarity was reversed and the right and left contact measurements were repeated. In some cases, the tables contain two values; one in parentheses. These latter values are the minimum relative energies which were required for the first appearance of avalanche photoconductivity. The non-parenthetical values are the minimum relative energies required for stable, reproducible avalanche photoconductivity.

There is no clear pattern to these results; that is, the minimum relative energies required for avalanche photoconductivity do not appear to be related to the polarity or, in the case of the mixed contacts, to type. This absence of a trend is not surprising in the ohmic contacts, if they are truly ohmic, but was not expected for the other contacts. However, the results do suggest that the minimum triggering energy is in general lower for the non-ohmic than the other contacts. There is a difference, however, in the behavior of the different types of contacts when the samples are pulsed repetitively. Table 5 contains the results of the

Table 1

Minimum Relative Pulse Energies in Microjoules
Required for Avalanche Photoconduction
Using One-Sided Ohmic Contacts

Right Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	34.8	34.8	20.2
2	6.4	14.3	20.2 (9.9)

Left Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	20.16	-	9.3
2	9.3	-	6.4

Table 2

Minimum Relative Pulse Energies in Microjoules
Required for Avalanche Photoconduction Using
One-Sided Schottky Contacts

Right Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	6.4	14.31 (9.9)	37.0
2	14.31	14.31 (3.2)	9.9

Left Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	3.2	-	9.9
2	9.9	-	37.0 (34.8)

Table 3

Minimum Relative Pulse Energies in Microjoules
Required for Avalanche Photoconduction Using
One-Sided Non-Ohmic Contacts

Right Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	1.2	3.2	2.4
2	9.9	1.7	0.6

Left Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	9.9 (4.6)	-	3.2
2	3.2	-	34.8

Table 4

Minimum Relative Pulse Energies in Microjoules
Required for Avalanche Photoconduction Using
One-Sided Mixed Contacts

Right Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	4.6 (1.2)	1.2	1.7
2	34.8	9.3	34.8

Left Contact Positive

Sample	Near Left Contact	Centered	Near Right Contact
1	4.6	-	2.4
2	53.7 (37.0)	-	70.0

Table 5

Maximum Number of Avalanche Photoconductive Pulses Before Pulse Shape Degradation

Ohmic

Sample	Number of Pulses	Dark Current (μA)
2	386	> 50
3	365	108

Schottky

Sample	Number of Pulses	Dark Current (μA)
2	96	> 50

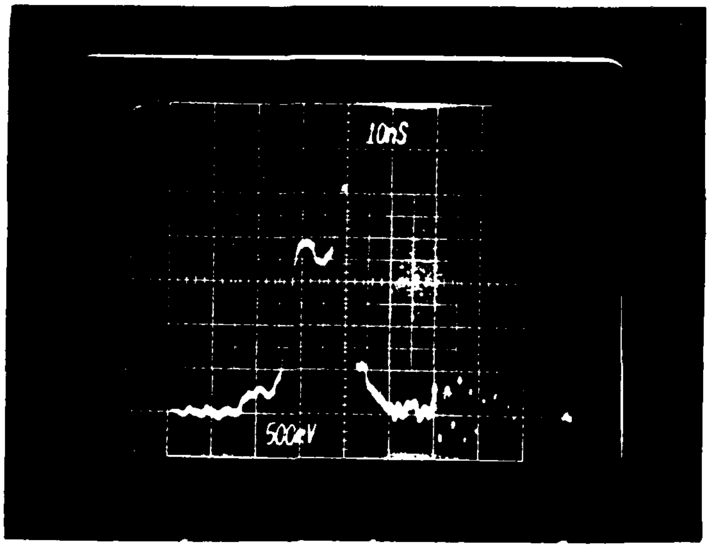
Non-Ohmic

Sample	Number of Pulses	Dark Current (μA)
1	40	20
2	58	50

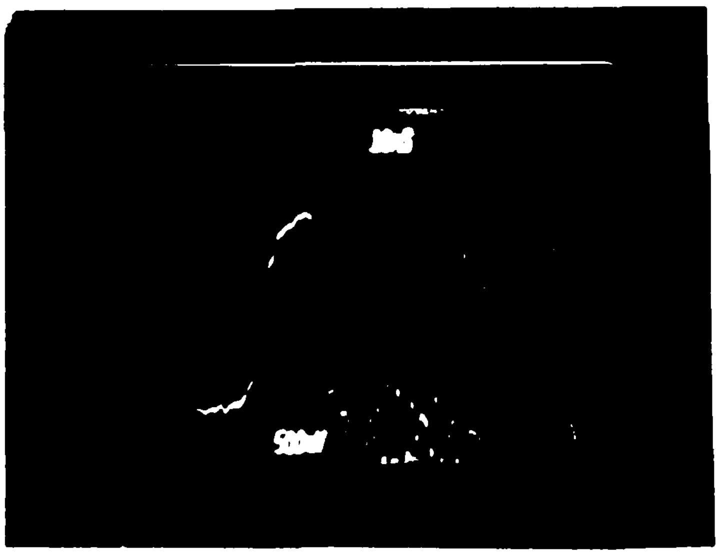
Mixed

Sample	Number of Pulses	Dark Current (μA)
2	175	100

repetitively pulsed measurements for a centered light spot; this tabulates the maximum number of avalanche photoconductive pulses which could be obtained before the pulse shape degraded. The value of the dark currents at the conclusion of the measurements have also been tabulated; these may be compared with the pre-pulse values, which were less than 1 μA. It is clear that pulse shape deterioration is least severe for the ohmic contacts and most severe for the non-ohmic contacts, with the Schottky and mixed contacts exhibiting intermediate behavior. The presence of a non-ohmic contact seems to accelerate deterioration. Figure 7 illustrates the type of pulse deterioration occurring for ohmic (Figure 7a) and non-ohmic (Figure 7b) contacts; all output pulses initially had the shape of Figure 6. In some cases, avalanche photoconduction was no longer observed after a large number of repetitions. The effect could be restored by stopping the excitation for several minutes and then beginning again. This may be a heating effect; however, the dark current, although decreasing slightly from its value at the extinction of avalanche photoconductivity, still remained quite high, arguing against cooling of the sample. There also appeared to be polarity effects associated with the mixed contacts. When the ohmic contact was made positive, pulse deterioration was observed; however, when the non-ohmic contact was made positive, a non-degraded pulse



(a)



(b)

Figure 7. Deteriorated output pulses for a) ohmic and b) non-ohmic contacts.

was obtained. Reversing the polarity again produced the deteriorated pulses. A short delay (around 50 ns) sometimes occurred between the initial triggering pulse and the onset of avalanche photoconductivity. This delay appeared for all the samples during repetitive pulsing (Figure 8) and increased for all the samples as repetitive pulsing continued.

When the samples were examined after the repetitive pulse measurements, it was found that a thin irregular line on the surface ran between the contacts; in some cases, the surface was discolored. This observation suggested the occurrence of surface breakdown and tracking; in one measurement, in fact, sparking between contacts has been observed during pulsing. A new sample was therefore fabricated to test for surface breakdown. This had three circular one-sided contacts, around 0.040 inch in diameter, two ohmic and one no-ohmic; one ohmic and one non-ohmic contact were adjacent to each other and separated from the second ohmic contact by 0.16 inch. The bias voltage, 12.5 KV (corresponding to an electric field of 31.2 KV/cm) was applied across the mixed pair consisting of the widely separated ohmic and non-ohmic contacts. A spark between the contacts was observed at every avalanche photoconductive pulse during repetitive testing. A surface track between the contacts could be seen at the conclusion of the measurement. When the non-ohmic contact was disconnected and the

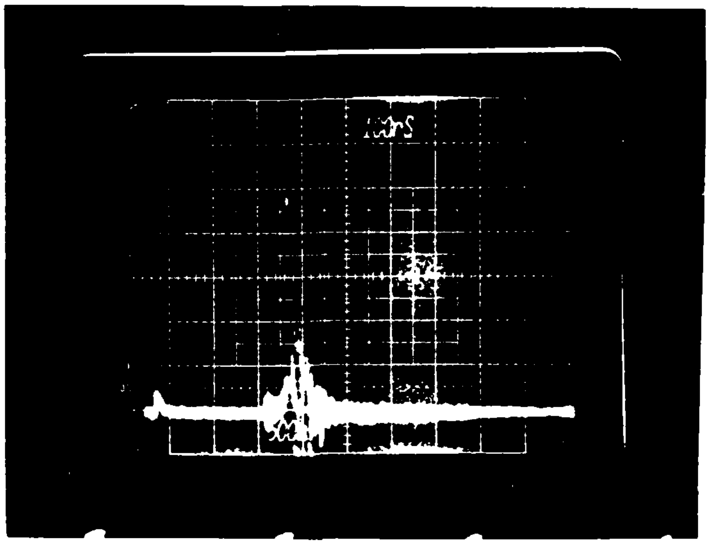


Figure 8. Delay between triggering light pulse and avalanche photoconductive pulse.

bias was placed across the ohmic pair (between which no track existed), the dark current was found to be 50 μA, indicating that the effect of the spark (or track) was extensive. It should be emphasized that no tracking of any kind was observed when two-sided contacts were used.

CHAPTER IV

CONCLUSIONS

The avalanche photomultiplication process appears to be related to surface breakdown, at least in these measurements. Although this event tends to obscure the effects of the contacts, the results of the one-sided contact measurements, which suggest that non-ohmic contacts are not as reliable in the long term as ohmic contacts, are supported by similar results from the two-sided contact measurements, where tracking did not occur. The two-sided contact configuration, in which tracking does not appear to be a problem, is a more desirable arrangement for evaluating contact effects. However, the problems associated with insulating the two-sided contact samples inhibited a more extensive series of measurements in this case. Also, the high voltages required to obtain the electric fields in the two-sided contact samples, and the associated limitations on the feedthroughs and cables, prevented a more complete evaluation. The problem of high voltage can be partially addressed by making the sample thinner, but a thin sample increases the difficulty of handling and possibly the probability of tracking. In any case, the results obtained here, although suggestive, require additional elaboration by more testing.

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