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Fabrication and Characterization of High-Voltage Ultra-Fast GaAs Photoconductive Switch*

Shi Wei(施卫)[1], Liang Zhenxian(梁振宪)[2], Xu Chuanxiang(徐传骧)[2]

(1 Applied Physics Department, Xi'an University of Technology, Xi'an　710048)
(2 Institute of Electrical Insulation, Xi'an Jiaotong University, Xi'an　710049)

Abstract　A process is first developed for the fabrication of high-voltage ultra-fast GaAs photoconductive switches with all-solid insulation technique. Multilayer transparent dielectric as passivation and insulation protection materials were deposited and coated on the surface of the GaAs switch. The ideal dark *I-V* characteristics of fabricated device are observed, the hold-off field strength reaches 35kV/cm. A laser of 200 ps pulse width was used in tests to examine the relations between electric field, rise time, delay and minimum optical trigger energy for switches which reached 30 kV/cm in a 50W transmission line with rise time as short as 200 ps. The lock-on effect observed in these devices are described.

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1　Introduction

Photoconductive semiconductor switches are commonly used as jitter-free, low inductance switches for pulsed power applications. A readily available photoconductive switch material is semi-insulating GaAs. This material has a large electron mobility which at room temperature is about as large as that for cryogenic silicon. Its dark resistivity is in the range of $10^7\Omega\cdot cm$, which compares favorably to that of Si ($10^4\Omega\cdot cm$). GaAs photoconductive switches exhibit sub-nanosecond pulses with high peak power and is of interest for ultrawide bandwidth applications for radar and electronic countermeasures[1,2]. Fruitful research activities show that photoconductive switches of some III-V semiconductors can operate in a nonlinear mode (or Lock-on effect, high-gain mode). The advantages of this mode operation are high efficiency, enhanced voltage capability, and fast risetime. In contrast to the linear mode where only one electron-hole pair is created by one photon, high-gain mode gets amplification of carriers during light triggering and greatly reduces optical

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Shi Wei (施卫)　was born in 1957. He received Ph. D. from Xi'an Jiaotong University in 1997. Now, he is an assistant professor in applied physics department of Xi'an University of Technology and works on the studies of optoelectronics and devices.

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trigger energy by a factor of up to 500~1000[3]. The power-switching capability of a photoconductor is given by the product of the current carrying capacity and its maximum standoff voltage. The dark current-voltage behavior of the switches is determined by a number of material, geometry, insulation, and fabrication parameters[4,5]. Applications of photoconductive switches for high power pulsed switching become practical, with operating characteristics of high off-state blocking voltage, high on-state peak current, and very fast (subnanosecond) opening/closing. In this paper, high-voltage ultra-fast SI-GaAs photoconductive switches fabricated with Au/Ge/Ni metallization ohmic contacts and protected with all-solid insulation technique are reported. The dark breakdown field limits of the switches and the switching characteristics including rise time, delay and its relationship to electric field strength, optical trigger energies have been discussed experimentally.

2 Switch Fabrication And Experiment

During the off-state, when the switch is not activated with light, the effective resistance is extremely high and there is no transfer of energy in the transmission line. The off-state resistance of the semicoductor switches may range as high as several megohms for GaAs. Once pulsed laser is introduced, carriers are produced and the semiconductor converts from an insulator to a conductor. Figure 1 shows the geometry and the details on design of the insulation structure of the switches used for this study. They consist of a rectangular semi-insulating GaAs slab of 0.6mm thick. This rather simple geometry was chosen because it can be mounted with the least inductance into a parallel plate transmission line structure that we used for testing. The Au/Ge/Ni ohmic contacts (black area in Fig. 1) with a rounded corner were placed on one face of the slab with different gap, from 0.5mm ~ 1.5cm. Insulation protection of the switch, different from high resistivity water or high pressure SF_6, has adopted multilayer transparent dielectric materials coated on the surface of the GaAs wafer. The first layer was thick Si_3N_4 film and the second layer was a new type of solid-state surface protection material named Organopolysiloxane Gel. Its insulated strength reaches 280kV/cm[6].

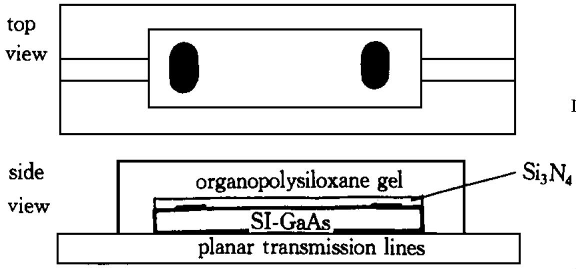


Fig. 1 Geometry and insulation structure of the switch

In order to ensure impedance matching, the sample was mounted on a 50Ω microstrip line. The dark current-voltage characteristic of the GaAs switches has been tested in dc conditions. Only one sample of a GaAs switch was able to be tested for dark breakdown. The entire test assembly is enclosed for optical and electrical isolation. Measurements are quasi-static, where the voltages were only applied until a steady current value is determined. The characteristics of current versus voltage are shown in Fig. 2.

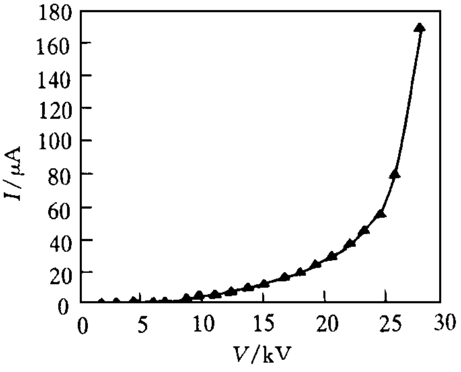
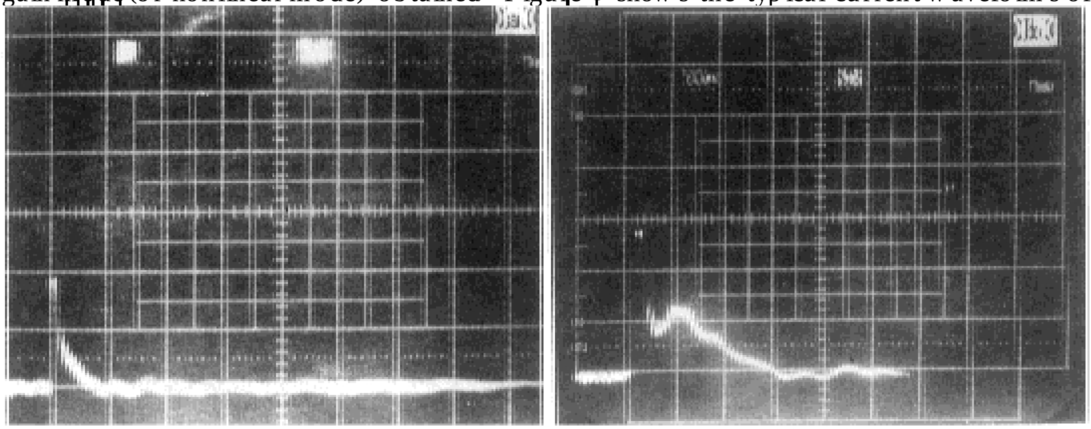


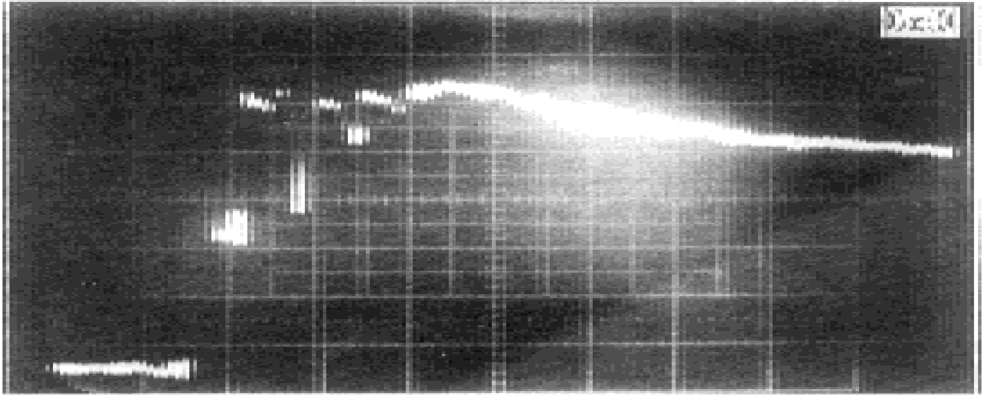
Fig. 2 Dark current-voltage characteristic of the switch

Instrumentation included mode-locked pulse laser system, Tektronix 7934 storage oscilloscope, light energy ratiometer (KSDP 2210-CAS-1), TS100 attenuator (DC～4GHz, 40dB), DELAY UNIT (HAMAMATSU C1097). For a GaAs switch of 3mm gap, when triggering by laser pulse energy of 43μJ, and electric field of 3.4kV/cm, appears linear mode, while applied filed strength reaches 8kV/cm, laser pulse energy 42μJ, high gain mode (or nonlinear mode) obtained. Figure 3 shows the typical current waveforms of



(a) Current waveform of a linear switch (3.4kV/cm, 43μJ. Y/div 1V, X/div 2ns)

(b) Current waveform of critical state of a switch (4kV/cm, 63μJ. Y/div 500mV, X/div 2ns)



(c) Current waveform of a nonlinear switch (8kV/cm, 42μJ. Y/div 1V, X/div 5ns)

Fig. 3 Typical current waveforms of linear, critical state and nonlinear switch linear, critical state and nonlinear switch. The rise time of the current pulse depends on triggering condition such as the electric field and the rise time of the laser pulse. In our series tests, the fastest rise time of the fabricated GaAs switch is about 200ps.

3 Results and Discussion

High gain photoconductive switches have a temporal evolution that is very different from that of linear switches. At low fields (below 3.5kV/cm), carriers are generated as the triggering light pulse was absorbed, the switch rise time is related to the laser pulse. Above 4.2kV/cm, different behavior is observed. Instead of following the light pulse shape, the switch turned on and stayed on (Lock-on) until most of the energy in the circuit is discharged. While the switch is on, the voltage across its contacts does not go to zero. Instead, it drops to a constant value, the Lock-on voltage, which is independent of the initial charging voltage. Further testing at reduced optical trigger energies shows that this high field switching mode can be initiated with less than 0.1% of the optical energy required for comparable linear switching. Some type of gain mechanism is being observed, because there are many more carriers generated than could be created directly by the incident photons. Furthermore, the switch continues to conduct for many recombination times folding after the optical trigger pulse has ended.

It is indicated by experiments that high gain switching only occurs when a sufficient bias voltage and optical trigger energy are simultaneously present. The relationships between the minimum trigger optical energy as a function of electrical field strength across the GaAs switch, these two thresholds are inversely related. The rise time of the electrical pulse obtained from high gain switching is independent of the rise time of the laser pulse. Although laser energy is a factor in determining the rise time, the strongest variable is the electric field. The turn-on delay to high field, nonlinear switching, like the risetime and minimum trigger energy, is inversely related to the average field across the switch at the time of activation. Far above the electric field threshold to trigger, the delay is less than 0.2ns. Near the threshold to triggering, this delay is greater than 1 ns. The delay time is measured with respect to the onset of linear photoconductivity in the switch. The variation with applied voltage is shown to roughly follow an exponential in the inverse of the applied voltage.

The intrinsically electrical breakdown field for GaAs is 200kV/cm. But in practical device, the attainable hold-off field is limited by some failure factors such as surface flashover, contact styles and thermal runaway etc. Many termination techniques including field shaping, dielectric coating, and surface preparations have and are being developed to continue to increase the breakdown strength of these devices. These tests are carried out in high resistivity water and high pressure SF_6 as well as with different coating and surface treatments. An important issue in the design and development of high-voltage and high-power GaAs switch is its surface insulation protection. Using a planar contact geometry flash-over occurred at electric fields above 12kV/cm. While the switches immersed in SF_6 at 25psi, the fields of up to 21kV/cm have been obtained. The best results of 143kV/cm, under pulse bias conditions, were obtained with GaAs switches in high resistivity water without metallized contacts. In SF_6, field of 26.6kV/cm was sustained for 30-second time interval. While in dc tests a Cr-doped GaAs switch withstood 16.8kV/cm for about 30 minutes. There are two ways to improve surface flashover of high-voltage lateral GaAs switches: ohmic planar contacts with optimal geometry and new type materials of surface insulation protection. We are using both methods to improve the dark hold-off field attainable with the GaAs switches. Ohmic contact to solid state switches critically determines the quality of the switch. It is the ohmic contacts that permit electrical access to the switch and ideally they should not affect its operation. In solid-state transparent insulation protection materials, Organopolysisoxane Gel has shown the greatest improvement overall. From the test results shown in Fig. 2 the largest hold-off strength fields of over 35kV/cm has attained with the coated device. The insulation protection of GaAs photoconductive switches are an important issue for high-voltage applications. Dark hold-off voltage is also a critical parameter to achieving high gain. For our slab geometry the critical factors are ohmic contacts with optimal rounded corner and solid-state dielectric coatings to prevent surface flashover. The largest hold-off strength of 35kV/cm of fabricated device was obtained. By use of all-solid insulation technique to fabrication of high-voltage GaAs switch made the device structure more simple and more practicable.

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