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Temporal development of electric field structures in photoconductive GaAs switches

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The temporal development of the electric field distribution in semi-insulating GaAs photoconductive switches operated in the linear and lock-on mode has been studied. The field structure was obtained by recording a change in the absorption pattern of the switch due to the Franz-Keldysh effect at a wavelength near the band edge of GaAs. In the linear mode, a high field layer develops at the cathode contact after laser activation. With increasing applied voltage, domainlike structures become visible in the anode region and the switch transits into the lock-on state, a permanent filamentary electrical discharge. Calibration measurements show the field intensity in these domains to exceed 40 kV/cm, which is greater than three times the value of the average applied field.

Photonic control of electronic circuitry has proceeded rapidly during the past few years.¹ The primary advantage of optically controlled semiconductor switches compared to other high power switches, such as triggered gas discharges, is their jitter-free, high speed (< 1 ns) response to laser pulses. Much of the present research effort is directed towards minimizing the optical energy required for switching. One way to increase the gain of the switch (the ratio of the energy transferred to the load to the trigger energy) is to utilize a nonlinear process known as the lock-on effect.² Lock-on occurs when a photoconductive switch is triggered into a state of permanent conductance. Lock-on has been studied primarily in direct semiconductors such as semi-insulating gallium arsenide but was more recently also observed in diamond switches.³ The mechanism of lock-on remains a matter of discussion, but experimental studies indicate that it is related to the occurrence of current filaments^{4,5} developing from regions of locally high electric field.⁶

In order to study the temporal development of the electric field distribution in photoconductive GaAs switches, we have developed a diagnostic technique which is based on absorption measurements at the band edge of the switch material.⁶ The absorption edge of insulators and semiconductors is shifted not only under the influence of electric fields (Franz-Keldysh effect) but also by changes in temperature, pressure, magnetic field, and carrier density. The effect is such that the local absorption of light with a wavelength corresponding to the band gap will increase with any increase in the value of these parameters. In photoconductive switches, the effects of electric fields and temperature are expected to dominate in the absorption pattern. The effect of electric fields on the optical absorption at the band edge can be described as photon-assisted tunneling through the energy barrier of the band gap. The probability P to find an electron at an energy ΔW below the conduction band is

$$P = \exp(-\Delta W/W_E), \quad (1)$$

where W_E is a function of the electric field strength E :

$$W_E = 1.5(m^*)^{-1/3}(e\hbar E)^{2/3}, \quad (2)$$

with m^* being the effective mass of the electron, e is its charge, and $\hbar$ is Planck's constant.⁷ Correspondingly, the absorption for below band-gap radiation increases with electric field intensity. This can be interpreted as a shift of the absorption edge by an energy W_E to lower photon energies or to longer wavelengths, respectively.

A rise in temperature in the photoconductor also causes a decrease in the band-gap energy. The change in energy ΔW_T can be fitted by the following empirical relation:⁸

$$E_g(0) - E_g(T) = \Delta W_T = aT^2/(T+b), \quad (3)$$

with $E_g(0)$ and $E_g(T)$ being the band gap at a temperature of zero and T , respectively. The material constants for GaAs are $a = 8.871 \times 10^{-4}$ eV/K and $b = 572$ K. A comparison of temperature and field effect shows that in GaAs a change in temperature by one degree Kelvin (at $T = 300$ K) has the same effect as varying the electric field at 3 kV/cm by 0.6 kV/cm, namely a shift in band-gap energy by about 1 meV. The effect of the plasma density on the shift in the band edge needs to be accounted for only in filamentary discharges, where the plasma density may exceed values of 10^{16} cm⁻³.⁹ Magnetic field and pressure effects can also be neglected in the range of operation for the investigated photoconductive switches.

The experimental setup is shown in Fig. 1. The switch sample consists of a 0.6 mm thick piece of semi-insulating GaAs (Furakawa Inc.) with a dark resistivity of 3×10^7 Ω cm and coplanar Au-Ge contacts spaced 2.3 mm apart. The sample was pulse biased up to voltages of 2.75 kV, corresponding to an average applied field of 12 kV/cm, using a 50 Ω transmission line pulser with 320 ns pulse duration. The power from the transmission line was switched into a 50 Ω load (R_L) with a 2.5 Ω current viewing resistor (CVR) in series. The temporal development of the switch voltage and current was recorded by means of two 500 MHz digitizers (Tektronix 7912).

The GaAs switch is activated by use of a Nd:YAG laser (Spectra Physics DCR 11) with a wavelength of 1064 nm and a pulse width of 7 ns. The radiation is attenuated by means of neutral density filters (NDF) and focused

FIG. 1. Schematic of the experimental setup.

with lens L-2 onto the entrance of a cylindrical waveguide of 6 mm diameter (HO-2) which serves as a spatial homogenizer for the laser radiation. After passing through the homogenizer the light hits the sample at an angle of 45° . The sample was probed with light from a laser diode array (LH-166, Laser Diode Inc.) with a peak power of 60 W and a pulse duration of 30 ns. The center wavelength of the 3.5 nm wide pulse is 906 nm at room temperature, which is at the long wavelength edge of the measured band edge absorption of the switch material. The probe laser light is sent through a spatial homogenizer HO-1 and is collimated by means of lens L-1. A spectral filter in front of a recording CCD camera is used to block the Nd:YAG radiation from the activating laser. The absorption pattern image of the GaAs switch at 906 nm is recorded by the CCD camera, and digitally processed by a computer. A Nd:YAG laser (1064 nm) was also used as the probe laser, but no absorption pattern was observed at this wavelength. The voltage pulse, the activation laser pulse, and the probe laser pulse can be shifted in time relative to each other, thereby allowing the temporal development of the absorption structure of the switch to be recorded before and after activation with a resolution of 30 ns, the pulse duration of the probe laser.

Depending on the applied voltage, the temporal development of the photocurrent shows two distinctively different patterns. Below a threshold voltage, which is dependent on switch material and the intensity of the activation laser, the photocurrent after activation decays with a time constant which is determined by trapping and recombination or by carrier sweep out (Fig. 2, bottom trace). For the material which was used in our experiment, and at an activation energy density of 0.5 mJ/cm^2 the threshold voltage was measured as 2.5 kV, corresponding to an average field of 10.8 kV/cm . The photocurrent in this voltage range scales approximately linearly with the laser intensity and voltage. Above the voltage threshold the switch does not recover to the initial high resistance state. Instead a permanent (lock-on) current flow is established within 50 ns after the activation source is turned off (Fig. 2, top trace). The forward voltage after the transition into the permanent conductance is, for the investigated material $1.4 \pm 0.3 \text{ kV}$, corresponding to an average field of 6 kV/cm with a statistical deviation of $\pm 20\%$.

FIG. 2. Oscilloscope traces of current flow in the linear mode at an applied voltage of 1.25 kV (bottom trace) and lock-on mode at an applied voltage of 2.75 kV (top trace). Also shown are the times at which the applied voltage pulse begins and ends.

Figure 3 shows absorption patterns for a switch, during and after biasing, operating below the lock-on threshold. No absorption was observed when the voltage was applied (up to the maximum voltage value in our study) before photoactivation. During and immediately after the photocurrent pulse a well-defined absorption layer with a thickness of $50\text{--}100 \mu\text{m}$ develops at the cathode [Fig. 3(a)]. In addition, structures begin to emerge into the gap. The cathode layer becomes more pronounced with time and, in many cases, seems to detach from the contact and form looplike and/or mushroomlike structures. When the voltage across the switch is removed the cathode layer disappears immediately. The absorption structures in front of the cathode layer, however, stay visible for several microseconds [Fig. 3(b)].

The dissipated Joule energy in the switch operating at 1.25 kV is on the order of mJ. This is not sufficient to raise the temperature in the regions with increased absorption by even a fraction of a degree. A temperature calibration showed that a change on the order of 50°C is required to

FIG. 3. Pictures showing variation of absorption structures with time in the linear mode at an applied voltage of 1.25 kV. The images were processed by subtracting a reference image obtained when no voltage was applied. The background gray level implies no absorption, darker areas signify absorption, and the white areas indicate the electrode regions. Pictures were taken at (a) 110 ns and (b) $10 \mu\text{s}$ after the rise of the voltage pulse.

FIG. 4. Sequence of pictures showing absorption structures and lock-on filament emission at an applied voltage of 2.75 kV. The images were processed in the same way as those for Fig. 3. Filament emission appears as the lighter areas in the gray background between the electrodes. Pictures were taken at (a) 120 ns, (b) 120 ns, (c) 200 ns, and (d) 250 ns after the rise of the voltage pulse.

be measurable in our system. It is therefore assumed that the observed structures are caused by space charge fields, which are developing due to the filling of traps by electrons injected at the cathode.

Increasing the voltage to 2.75 kV, corresponding to an average electric field of 12 kV/cm, causes the switch in over 90% of the shots to transit into the lock-on mode. The transition into a permanent current mode is always related to the occurrence of a luminous filament bridging the gap between the contacts.⁵ The filament emission contains radiation at the same wavelength as the probe laser and creates a time integrated image on the CCD camera, superimposed on the time resolved absorption patterns.

Figure 4(a) shows the absorption structure 20 ns after laser activation at an applied voltage of 2.75 kV, for the rare case in which lock-on did not occur. The structures at the cathode are of the same type as seen at lower voltages, only more pronounced and generally reaching further into the gap. In addition to the cathode, related structure absorption bands emerge in the anode space at higher voltages. Their intensity varies from shot to shot; their shape, however, is fairly reproducible. If the switch does not tran-

sit into the lock-on state the intensity of the anode absorption bands decays in time on the order of 100 ns, following the decay of the switch current rather than the switch voltage.

Pictures obtained at the same probe time, but in which lock-on subsequently occurred show very similar absorption structures as well as the filament [Fig 4(b)]. The filament seems to act as a short which removes the initial space charge structures, evidenced by a decrease in the intensity or even disappearance of the absorption patterns. Pictures taken at probe times after the onset of the lock-on current show this shorting effect [Fig. 4(c)]. Dark spots inside the filamentary channel indicate local heating with temperatures greater (probably much greater) than 50 °C [Fig. 4(d)], which can lead to permanent damage. The damaged region was found to increase with every filamentary discharge passing through this area. Most of the damage, however, did not occur inside the gap but rather at the contacts.

Measurements of the dependence of absorption on electric field intensity at a probe wavelength of 908 nm indicate that the field strength in the observed domains is greater than 40 kV/cm.¹⁰ At these fields impact ionization of deep traps in GaAs becomes likely, locally generating free carriers which may lead to the development of a current filament and consequently lock-on.

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