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GaAs photoconductive closing switches with high dark resistance and microsecond conductivity decay

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Silicon-doped n-type gallium arsenide crystals, compensated with diffused copper, were studied with respect to their application as photoconductive, high-power closing switches. The attractive features of GaAs:Cu switches are their high dark resistivity, their efficient activation with Nd:YAG laser radiation, and their microsecond conductivity decay time constant. In our experiment, electric fields as high as 19 kV/cm were switched, and current densities of up to 10 kA/cm^2 were conducted through a closely compensated crystal. At field strengths greater than approximately 10 kV/cm, a voltage "lock-on" effect was observed.

Photoconductive semiconductor switches are commonly used as jitter-free, low inductance switches for pulsed power applications.[1] 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.[2] Its dark resistivity is in the range of $10^7\ \Omega$ cm, which compares favorably to that of Si ($10^4\ \Omega$ cm). However, due to the high electron-hole recombination rate, the decay time of the conductivity is on the order of tens of nanoseconds or less. A GaAs closing switch conducting for a time in excess of the recombination time constant requires continuous illumination, a serious impracticality at the high optical power levels required for pulsed power switching.

One way to modify the properties of GaAs so that the characteristic conduction time is increased relative to that of typical semi-insulating GaAs is to compensate Si-doped, n-type GaAs crystals with diffused copper (a deep acceptor). It is thereby possible to generate GaAs:Si:Cu crystals with dark resistivities as high as $10^8\ \Omega$ cm at room temperature.[3]

Because of the properties of the deep levels associated with copper in GaAs, the compensation of n-type GaAs with copper leads to long photoconductivity decay time constants. There exist two copper-related deep level defects (Cu_A and Cu_B) in GaAs.[4] The Cu_B level, which is of main interest for our concept, is at 1.07 eV below the conduction band.[4] In Si-doped GaAs compensated with Cu the majority of the Cu acceptors are ionized.

Photoionization of trapped electrons from the deep Cu level into the conduction band is possible with Nd:YAG laser radiation. In addition, electron-hole pairs are generated by two-step ionization via vacant deep Cu centers. However, electron-hole pairs have a short lifetime in semi-insulating GaAs; therefore, after illumination with a short Nd:YAG laser pulse the free-carrier density should initially exhibit a rapid decay. As time goes on, however, the conductivity decay stabilizes to a new and much longer time constant due to the small electron capture cross section of the deep Cu center (8×10^{-21} cm^2 at room temperature[4]). In order to terminate the conductive phase on command a second photon source with low-energy photons ($1.04\ \text{eV} > h\nu > 0.44\ \text{eV}$) can be used to release the trapped holes in the Cu level and thus stimulate their recombination with electrons in the conduction band.[5]

The crystal used in this investigation was grown using the horizontal Bridgman technique with a silicon doping density of 5×10^{16} cm^{-3}.[6] Copper was evaporated onto both faces of the crystal in layers of thickness less than 1 μm. The crystal was then annealed in a temperature-controlled furnace for 2 h at 575 °C ($\pm$ 1 °C). Nickel-gold-germanium contacts were then formed in a planar geometry on one face of the sample. The contacts were demonstrated to be injecting contacts by measuring the dark I-V characteristics of the sample up to a maximum voltage of 1.3 kV. From these characteristics the resistivity of the material at room temperature is measured to be approximately $3\times10^4\ \Omega$ cm. The sample measures 4 mm$\times$6 mm and is 0.22 mm thick. The contacts are separated by a 2.5 mm gap and are 3 mm wide.

In order to determine the activation energy of the defect state controlling the dark conductivity of the sample, measurements were made of the dark conductivity as a function of sample temperature. When the sample temperature was reduced from 293 to 241 K, the sample conductivity decreased by almost two orders of magnitude. When the dark conductivity was plotted versus reciprocal temperature, a straight line was observed indicating that a single level controls the sample's dark conductivity over this temperature range. The activation energy calculated from the slope is 0.49 eV, which is roughly consistent with the activation energy of Cu_B assuming the sample is p type.

A Nd:YAG laser (wavelength = 1064 nm, photon energy = 1.1 eV) with a pulse energy of approximately 120 mJ and a pulse duration of 10 ns (FWHM) was used to activate the switch. The sample was illuminated on the noncontact side with a spatially uniform beam generated with a simple beam homogenizer.[7] The electrical system used to test the

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switching characteristics of the crystal consisted of a 50 Ω pulse-forming line (PFL), with a two-way transit time of 160 ns, in series with a load and the GaAs switch. The PFL is pulse charged by a Marx bank to peak voltages ranging from 1.5 to about 5 kV.

Figure 1 demonstrates a typical switching event for peak fields less than about 10 kV/cm. Upon application of the laser pulse (the beginning of the pulse is indicated by the arrow), the current rapidly rises to 55 A and then decays to a long-time constant "tail current," which after 160 ns has settled to 25 A. This represents an approximate tail current density of 3.7 kA/cm^2. This current density was achieved with a total illumination energy on the active area of the sample (the interelectrode region) of approximately 4 mJ. Of this only a small fraction was actually absorbed (i.e., in the 1% range) due to the large absorption length of GaAs at this wavelength. Thus, much larger currents could have been conducted (subject to limitations imposed by the contacts) for the same laser energy had we used a thicker sample.

Other experiments conducted with similar samples at lower voltages indicate the time constant for the tail current to be in the tens of microseconds.[8] The observed temporal photoresponse of this compensated GaAs:Si:Cu crystal is in agreement with the results of rate equation calculations where all the processes which lead to the population and depopulation of the various deep levels are considered.[9] The approximate conductivity of the sample on the "tail" of the photoresponse was 1 $(\Omega\ cm)^{-1}$, which falls within the range calculated for the sample [0.5–6 $(\Omega\ cm)^{-1}$] given the uncertainties in the laser photon flux and the deep level configuration of the sample.

As the peak field is increased above 10 kV/cm, however, a different effect is observed. At these fields the sample typically goes into "lock-on," a state that is typified not by a slowly decaying conductivity, as in the tail current, but by a constant voltage, as in a Zener diode. Our experiments indicate a lock-on voltage of 1.2 kV for this sample, which corresponds to an average field of 4.8 kV/cm. Lock-on has been observed in other semi-insulating GaAs materials and InP at fields comparable to that observed here.[7,10] Lock-on is believed to be associated with the formation of stable space-charge domains created by the negative differential conductivity observed at high fields in GaAs (the Gunn effect).[10]

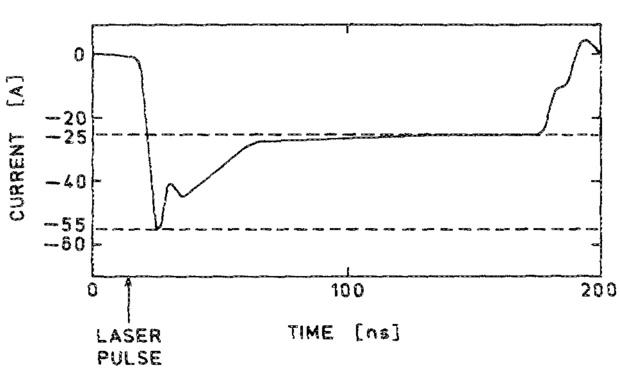

FIG. 1. Sample current vs time (note that the collapse of the current after 160 ns is due to the end of the transmission line voltage pulse).

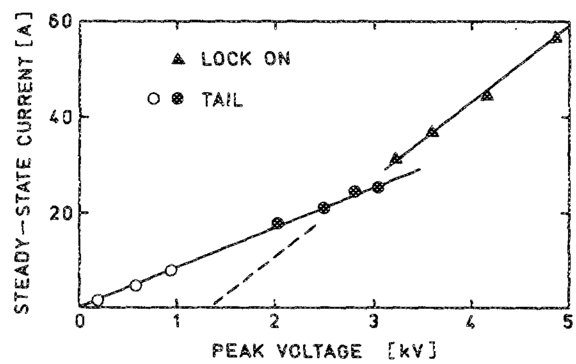

FIG. 2. Peak voltage vs tail/lock-on current. Open circles represent data measured with a low-voltage 50 Ω apparatus, while closed symbols represent data obtained with the higher voltage 50 Ω apparatus described in the paper.

Figure 2 is a plot of the peak charging voltage of the PFL versus the "steady state" current through the sample after the laser has initiated conductivity. Open circles indicate data measured with a slightly different low-voltage 50 Ω apparatus. The graph demonstrates that two regimes can be differentiated by their unique voltage-current characteristics. The tail current data are correlated with a straight line of small intercept. This is to be expected as the mechanism involved produces persistent conductivity; therefore, the *V-I* curve should be a straight line with zero intercept and a slope equal to the total resistance of the circuit. Lock-on represents constant voltage operation,[7] thus the *V-I* curve should break to a new line, at the higher peak voltages, that has an intercept on the voltage axis equal to the lock-on voltage of the sample.

The experimental results demonstrate that compensated GaAs:Si:Cu, if used as a photoconductive closing switch, can be activated with Nd:YAG laser radiation at 1.06 μm. The decay time of the conductivity is, after an initial drop with a 1/*e* time of about 30 ns, in the range of tens of microseconds. Thus a GaAs:Si:Cu switch has a conductivity decay time constant comparable to that achieved with bulk silicon closing switches, but with the advantages of using GaAs, such as high dark resistivity and high electron mobility. The parameters at which this device was tested (kV/cm and kA/cm^2) demonstrate that GaAs:Si:Cu can be operated at levels typically found in pulsed power circuits switched with bulk semiconductors.

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