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Bistable behavior of the dark current in copper-doped semi-insulating gallium arsenide

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The dark current characteristics of gallium arsenide doped with silicon and compensated with diffused copper were found to have a pronounced region of current controlled negative differential conductivity (ndc) similar to the characteristics of a thyristor. The resistivity of the semi-insulating semiconductor was measured to be 10^5 Ω cm for applied voltages up to 2.2 kV, which corresponds to an average electric field of 38 kV/cm. At higher voltages, a transition to a stable high current state was observed with a current rate of rise exceeding 10^{11} A/s. There is evidence of the formation of at least one current filament during this transition. A theoretical model based on drift diffusion and boundary conditions that allows double carrier injection at the contacts has been used to show that the observed negative differential resistance is due to the filling of deep copper acceptors. The model also shows that the ndc curves may be tailored by adjusting the copper concentration. Doping of GaAs with various concentrations of copper was shown to change the dark current characteristics in a way predicted by the model.

INTRODUCTION

The high dark resistivity of semi-insulating GaAs, which is often used as a figure of merit for semi-insulating semiconductors, is only defined for relatively low voltages. The ohmic region of the dark current in semi-insulating GaAs reaches up to voltages which correspond to average electric fields in the kV/cm to several tens of kV/cm range, dependent on the fabrication technique, doping, and the contact spacing. Above the so-called trap-filled limit voltage, V_{TFL}, the dark current rises dramatically with voltage.[1,2] This well known behavior of semi-insulating GaAs can be explained as a trap filling effect due to single carrier injection,[2] generally electron injection, in samples with only one type of contact (*n* or *p*). With increasing current density, the probability for injection of the second type of carriers, generally holes, rises due to the buildup of space charges in the vicinity of the non-injecting contact.[3] Eventually, double injection can be expected, leading to filament formation.

In semi-insulating semiconductors that contain large concentrations of deep acceptors, and with hole capture cross sections much larger than electron capture cross sections, it has been predicted that double injection leads to negative differential resistivity regions in the dark current characteristics.[2] A material which satisfies these capture cross-section conditions is silicon doped, copper compensated gallium arsenide (GaAs:Si:Cu). The base material is silicon doped GaAs with silicon concentrations in the range from 10^{16} to 10^{17} cm^{-3}. GaAs:Si is an *n*-type semiconductor, and it can be compensated with diffused copper, which forms several deep acceptors.[4] Thermal annealing at temperatures of 560 °C for 10 h with a thin layer of copper (1 μm) deposited on the surface of the GaAs:Si wafer, has resulted in a semi-insulating material with resistivities of up to 10^7 Ω cm. The compensated semiconductor is used as switch material in bulk optically controlled switch (BOSS) devices, which are a new type of photoconductive switch that can be turned on and off using light of different wavelengths.[5,6] For best switching results, the semiconductor needs to be slightly overcompensated with copper (slightly *p* type).[7] This is obtained by increasing the annealing temperature above the value required for complete compensation.

We have investigated experimentally the temporal development of the dark current in GaAs:Si:Cu over a wide range of voltages which correspond to average electric fields of up to 103 kV/cm. A numerical code which includes the effect of the dominant defects and traps in semi-insulating GaAs[8] was used to model the dark current characteristics, and to predict its dependence on type and concentration of deep centers. This information is of importance for the design of electronic devices, such as photoconductive switches or integrated circuits, where the insulating properties of GaAs are important.

EXPERIMENT

Two silicon doped, copper compensated gallium arsenide samples were studied with respect to their dark current characteristics. The low voltage dark resistivity was 1×10^5 Ω cm for sample No. 1, and 2×10^6 Ω cm for sample No. 2. Using the results of the fabrication procedure, it is assumed that No. 1 contained a higher concentration of deep acceptors than No. 2. The samples were rectangular in size with an area of 5 mm×5 mm, and thicknesses of 0.058 and 0.061 cm, respectively. The circular contacts with a diameter of 3 mm, were placed on the top and bottom face of the sample. They were formed using a gold-

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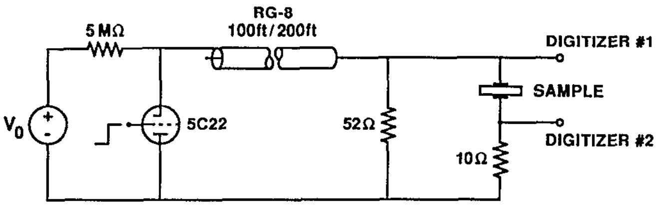

FIG. 1. Circuit used to measure the dark current-voltage characteristics of GaAs:Si:Cu samples.

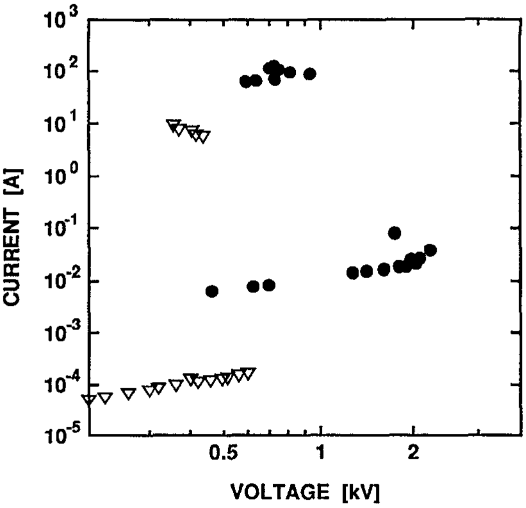

FIG. 3. The dark current-voltage curves for GaAs:Si:Cu sample, No. 1 (solid dots) and No. 2 (open triangles).

germanium alloy,[9] deposited by thermal evaporation and annealed under N_2 at 450 °C for 10 min.

The dark current measurements were carried out using a voltage pulse generator, shown in Fig. 1, which produces voltage pulses of 300 or 600 ns depending on the length of the RG-8 cable, which was used as the pulse forming network. The current through the circuit was obtained by measuring the voltage across the 10 Ω current viewing resistor (CVR), which is in series with the GaAs:Si:Cu. The voltage across the GaAs:Si:Cu and CVR was measured in order to obtain the sample voltage. The current and voltage measurements were made using two Tektronix 7912 digitizers. The sample was mounted in a 50 Ω microstrip line in order to maintain the necessary circuit bandwidth. To prevent surface flash-over, the 50 Ω microstrip line was mounted in a quartz pressure chamber filled to about 25 psig SF_6.

The dark current increased monotonically with voltage for applied voltages up to 600 V (9 kV/cm) for No. 2, and 2.2 kV (38 kV/cm) for No. 1. Above these voltage values, a dramatic change in dark current was observed. Figure 2 shows the temporal development of both sample current and voltage (sample No. 1) for an applied voltage of 3.3 kV. For about 120 ns, the dark current is on the order of 100 mA (not within the resolution of current scale in Fig. 2), and then transits into a high current mode with current levels three orders of magnitude above the initial value at only slightly lower voltages. In Fig. 3, the maximum current values are plotted versus the corresponding voltage data. Sample No. 1, which is more *p* type (or more overcompensated) than No. 2, transitions into the high current state at a much higher voltage. The difference in hold-off voltage (maximum voltage with subampere dark current) is even more striking when compared to liquid-encapsulated crystal (LEC) grown semi-insulating GaAs of the same thickness,[1] which only holds about 200 V. It should be noted that the highest measured value of the voltage at low currents is not necessarily the maximum hold-off voltage, but is determined by the load line of the electrical circuit. With higher impedance circuits, even larger values of hold-off voltage might be measured.

The delay time for the onset of the dark current development is strongly dependent on the applied voltage. This is shown in Fig. 4. In this figure, the delay time is defined as the time difference between the onset of the high current

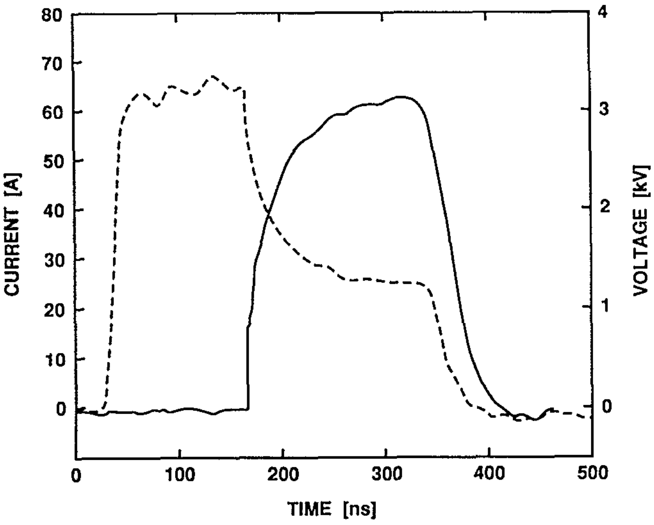

FIG. 2. The temporal development of the dark current (solid line), and voltage (dashed line) for sample No. 1.

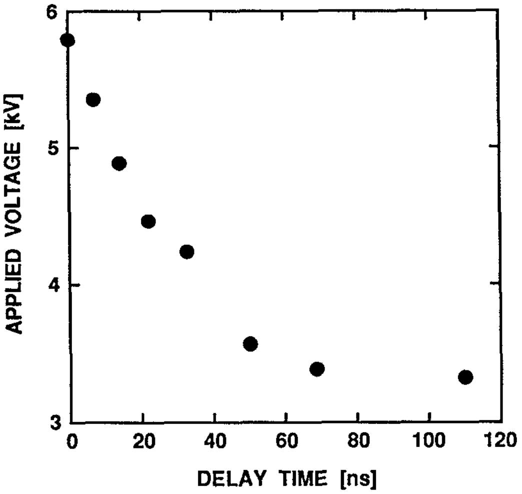

FIG. 4. The dependence of the delay time for the onset of high dark current flow on the applied voltage.

pulse and the time at which the peak voltage is reached (see Fig. 2). Zero onset time implies that the current development occurs immediately after the peak voltage is reached (on the time scale of the experiment). The risetime of the dark current transition is also dependent on the applied voltage. For applied voltages of 6 kV (103 kV/cm), the initial current rise to 30 A occurred in less than 500 ps, which corresponds to a current rise of greater than 10^{11} A/s.

MODEL

The steady-state dark current characteristics of silicon doped copper compensated gallium arsenide, was modeled using the drift-diffusion equations.[8] The GaAs crystal was assumed to contain EL2 centers (activation energy = 0.8 eV) with a concentration of 5×10^{15} cm^{-3}. Copper is known to form several deep acceptors in GaAs:Si, two of which are called $\mathrm{Cu_A}$ and $\mathrm{Cu_B}$. The activation energies for $\mathrm{Cu_A}$, and $\mathrm{Cu_B}$ are 0.14, and 0.44 eV, respectively.[10] The electron and hole capture cross sections of $\mathrm{Cu_A}$, $\mathrm{Cu_B}$, and EL2 are as follows: $\mathrm{Cu_A}$: 2.7×10^{-17} cm^2, 4×10^{-15} cm^2; $\mathrm{Cu_B}$: 8×10^{-21} cm^2, 3×10^{-14} cm^2; EL2: 8×10^{-13} cm^2, 3×10^{-16} cm^2, respectively.[10,11] Note that for the copper centers, the hole capture cross sections are much larger than the electron capture cross sections. This condition is used in an analytical analysis by Lampert[2] which shows negative differential resistance in the dark current-voltage characteristics of doped GaAs using double injection conditions.

Double injection is a condition which allows the free flow of electrons through the cathode contact, and holes through the anode contact. In other words, the electric field is zero at the contacts. Experimentally, this condition is not satisfied at low current densities when Au:Ge contacts are used on GaAs due to the *n*-type Ge dopant, which creates a *p-n* barrier at the anode. At high current densities, however, the boundary conditions may change from single injection to double injection as the anode barrier is overcome.[3] This holds particularly when filamentation occurs, which in turn is related to the experimentally observed negative differential resistivity.

The results of the numerical calculations are shown in Fig. 5. There is clearly a qualitative agreement between this curve and the experimentally obtained current-voltage curves. By proper choice of the defect and impurity concentrations and their capture cross sections which are only vaguely known, it is certainly possible to also get a quantitative agreement of model and experiment. However, this is not the purpose of this calculation. The purpose is to demonstrate the strong effect of deep centers on the dark current of semi-insulating semiconductors, which allows us to tailor devices with very peculiar dark current characteristics, such as these with negative differential resistance. The model also accurately predicts the variation in the negative differential resistivity with the concentration of copper in GaAs. By reducing the copper concentration, the ndr becomes less pronounced and disappears completely if all copper centers are removed.

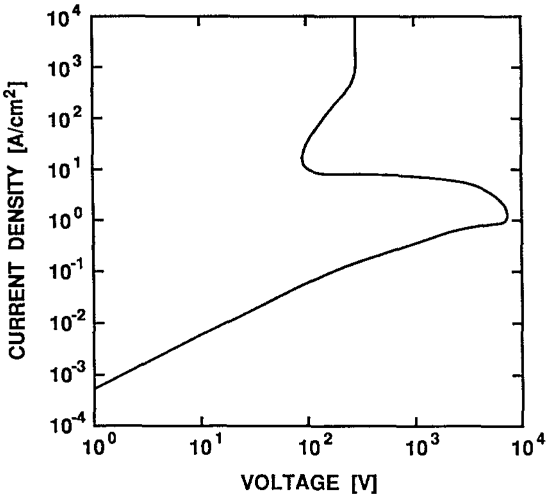

FIG. 5. The computed dark current-voltage curve.

SUMMARY

The temporal development of the dark current in silicon doped, copper compensated, GaAs was measured. At voltages that correspond to average electric fields in the tens of kV/cm range, the dark current changes from a low current mode into a high current mode with a current ratio of three to four orders of magnitude. At applied voltages of more than 2 kV across the 0.6 mm sample, these transitions from the mA range to the tens of A range occurred on a subnanosecond timescale.

The corresponding current-voltage curve shows a pronounced region of negative differential resistance. The extent of this region depends on the doping density of copper. Specifically, for a given silicon concentration, an increase in copper density causes a more pronounced S-shaped region of ndr. The highest hold-off voltage before the transition into the high current range was measured to be 2.3 kV across a 0.6 mm sample, which corresponds to an average electric field of 40 kV/cm. These are values which are generally only obtained with semi-insulating GaAs which is heavily damaged by neutron irradiation. The material which we have studied has, in spite of this high hold-off voltage, electron mobilities of about 4000 cm^2/V s.[11] The measured negative differential resistance in GaAs:Si:Cu explains the occurrence of current filamentation in this material.[12,13] Samples destroyed during the experiments were found to have been damaged by current filaments with cross sections of 10^{-3} cm^2. Using the measured current values, current densities as high as 10^5 A/cm^2 may have developed through such a filament. The closely compensated material was damaged by only a few of the high current pulses; however, the over-compensated material was not damaged after many high current pulses.

The shape of the dc current-voltage curve can be explained by considering trap filling processes.[1,2] Due to the large hole capture cross section of the copper centers, the hole lifetime at low voltages will be less than the hole transit time from positive to negative contact. With increasing voltage, however, the hole lifetime will increase due to the increased number of filled traps. Eventually the hole lifetime will reach and exceed the transit time, and because of the establishment of an electron-hole plasma in the entire bulk, a large increase in current at reduced voltages will result.

This mechanism is also assumed to cause lock-on in GaAs:Si:Cu.[6,14] After illumination of semi-insulating GaAs with lasers or electron beams, the current continues to flow even after termination of the ionization source, if the voltage across the sample exceeds a certain level, which is in the range of several kV/cm to several tens of kV/cm. The radiation only speeds up the process of hole-trap filling, and therefore reduces the delay for the transition into the high dark current phase essentially to zero.

The numerical model describes the qualitative behavior of the dark current very well. The accuracy of the model is limited by our knowledge of the deep center parameters in semi-insulating material. The model does, however, allow us to predict changes in the electrical characteristics of semi-insulating GaAs which can be expected when the type and concentration of deep centers is varied. This allows us to tailor semi-insulating semiconductors with respect to their electrical characteristics. This is of importance for devices where the performance is strongly dependent on such parameters as hold-off voltage, and dark resistance. The high hold-off voltage and the S-shaped dark current curve of GaAs:Si:Cu are of particular importance to high power photoconductive switches.

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