Reaction Time to Voltage Pulses Applied to Semiconductor Impact Ionization Breakdown

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The electric avalanche breakdown in semiconductors exhibits many features of a phase transition. In this paper, we introduce time-resolved measurements performed during the transition from a low to a high conducting state as reaction to a sudden change of the control parameter (i.e., the voltage bias).

Nowadays, many interesting questions posed in science are connected to the phenomenon of structure formation. There exists a large variety of structure-forming processes in diverse disciplines, like biology, medicine, mathematics, and physics. For the case of semiconductor physics, we know structures as high-electric-field domains and current filaments as a consequence of the Gunn instability and electric breakdown effects, respectively. So far, the current filaments generating during low-temperature impurity impact ionization breakdown have been visualized under steady state conditions [1]. To get more information about the nucleation of these structures, our experimental set-up is extended to time-dependent external parameters.

The experiments were performed on single-crystalline p-type germanium with an impurity concentration of about 3×10^{14} cm^{-3} and dimensions ranging from some hundred microns to a few millimeters. The material is homogeneously doped with indium (resulting to an acceptor level at 11.2 meV). The samples are furnished with ohmic contacts made by evaporating and alloying aluminum or by boron ion implantation. At temperatures of the liquid helium, about all charge carriers are frozen out at the impurity atoms. These impurity atoms can be ionized through inelastic scattering processes by hot electrons heated up by an external electric field. The generation of mobile charge carriers overcomes the recombination at a critical field of about 5 V/cm. Now the nondestructive avalanche breakdown sets in, leading to a negative differential conductance (see the schematic current-voltage characteristic in Fig. 1) accompanied by the formation of plasma-like current filaments. Their nucleation process is subject of the following experiments.

The electric circuit consists of a series combination of a pulsed voltage source V_0, a load resistor R_L, and the sample. The voltage was switched from zero to a well-defined upper level V_H. The voltage drop over the

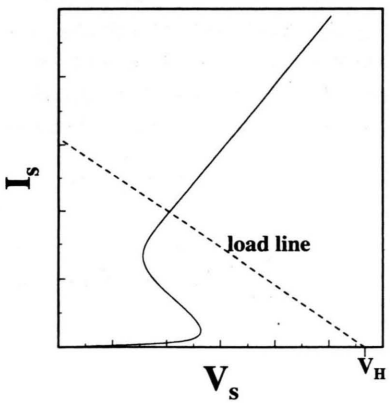

Fig. 1. Scheme of an S-shaped current-voltage characteristic with negative differential conductance.

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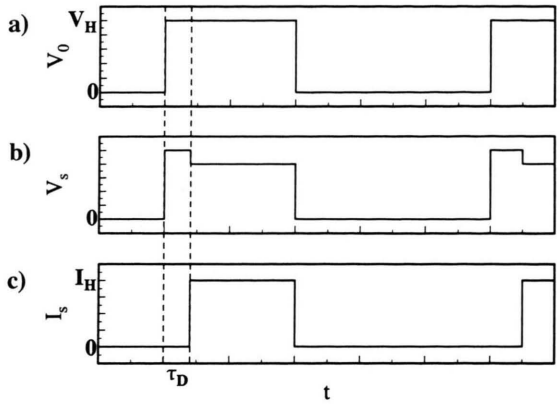

Fig. 2. Scheme of time traces of the signals bias voltage (a), sample voltage (b), and sample current (c). The sudden rise of the sample current leads to a sharp collapse of the sample voltage. The time interval between the rise of the bias voltage and that of the sample current is defined as delay time τ_D.

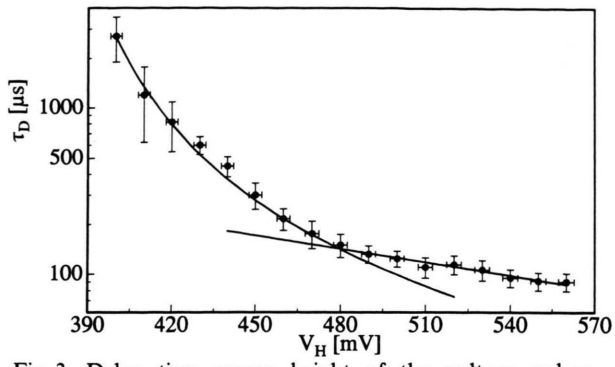

Fig. 3. Delay time versus height of the voltage pulses applied. Full dots correspond to the mean, the bars to the variance of the measured data. Solid curves are fitted for different branches. The delay time τ_D diverges when the upper level voltage V_H approaches the critical voltage V_c. It exhibits a quadratic pole (see left part fitted with a quadratic function) and a crossover to an exponential behavior for higher values of the excess voltage (see right part fitted with a logarithmic function). The system parameters are: sample dimension $0.9 \times 0.6 \times 0.3$ mm^3, load resistance $R_L = 1\text{k}\Omega$, and temperature $T = 4.2$ K.

load resistor yields to the sample current I_s. The voltage drop V_s was measured along the sample. The sketch in Fig. 2 gives an idea for the time evolution of the above three signals. The quantity investigated is the time delay τ_D between the rise of the external voltage V_0 and that of the sample current I_s. It can be looked at as the characteristic time the sample reacts to the parameter change. Figure 3 shows the dependence of the upper voltage level V_H upon the delay time τ_D. At lower excess voltage V_e (i.e., the difference between V_H and the critical voltage V_c) we have $\tau_D = \alpha/V_e^2$. Note that a similar result was already observed for the case of a completely different sample material, namely, blue bronze [2]. At higher excess voltage, a crossover to the dependence $\tau_D = \beta \exp(-V_e)$ can be observed.

We have modeled the qualitative behavior of the reaction time τ_D with a homogeneous system taking into account the ground and first excited states of the impurity atoms. However, compared to the experimental results, the calculated delay times turned out to be much faster. There is need to use a model that a priori incorporates the capability of structure formation. We think of a spatially inhomogeneous system recovering the necessary additional degrees of freedom from the space domain.

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