Spatial aspects connected with the nucleation process of current filamentation in *p*-type germanium

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We observe spontaneous current oscillations developing during low-temperature impact ionization breakdown of slightly doped *p*-type germanium under the influence of a small transverse magnetic field. The spatiotemporal dynamics manifests in the nucleation, the continuous displacement perpendicular to the direction of the magnetic field, and the annihilation of a current filament. We concentrate on the spatial aspect of the nucleation process. An extension of an experiment, in which the lateral filament dynamics can be detected, allows us to study the spatial behavior of filaments under different preconditions. These experiments reveal a strong influence of a preceding filament on the nucleation site of the subsequent one. Nucleation is preferred in sample regions with the longest absence of the filament and, therefore, most probable on the side opposite to the annihilation region of the previous filament. The ''memory'' of the sample extends up to few seconds, but can be erased by illumination. [S0163-1829(96)03944-6]

I. INTRODUCTION

Low-temperature impact ionization breakdown in semiconductors manifests in a strongly nonlinear curvature of the current-voltage characteristic (often accompanied by an S-shaped negative differential conductance). The current flow can simultaneously exhibit spontaneous oscillations in the temporal and filamentation in the spatial domain.[1–4] The system dynamics is highly sensitive to the smallest variations of such control parameters as the electric field E, the magnetic field B, and the temperature T. In particular, the transverse magnetic field (oriented perpendicular to the electric field) has the potential to unveil the complex interplay underlying the spatiotemporal structure formation. In the simplest case, current filaments are deflected to a direction perpendicular to the electric and magnetic field (given by the Lorentz force). The resulting transverse motion of the filaments can be deduced from measurements of the electrostatic potential at different sites of the bulk semiconductor.[5] Other experimental activities in this framework, for example, have been carried out by Prettl and co-workers.[6] An extended theoretical ansatz was given by Schöll and co-workers.[7]

II. EXPERIMENT, RESULTS, AND DISCUSSION

The experimental setup used is shown in Fig. 1. The bulk semiconductor single crystal (material *p*-type Ge, acceptor concentration $N_A = 3\times10^{14}$ cm^{-3}, size $3\times5\times0.2$ mm^3) is provided with planar Ohmic contacts (contact distance 900 μm, contact width 600 μm). At the central position of each contact area (denoted by 1 and 4), a constant voltage supply is connected to the sample via a load resistor $R_L = 100\ \Omega$ (where the current I_s is measured). One of the contact pads contains two additional bonds (denoted by 2 and 3). They have a distance of 200 μm from point 1. The resistance between the outer contact and the inner one is about a few hundred Ohms. These additional probes are used to monitor independently the corresponding partial voltage drops V_l and V_r (from point 2 to point 4 and from point 3 to point 4, respectively). A constant magnetic field perpendicular to the broad surfaces of the sample and the direction of the current flow is applied through a superconducting sole-

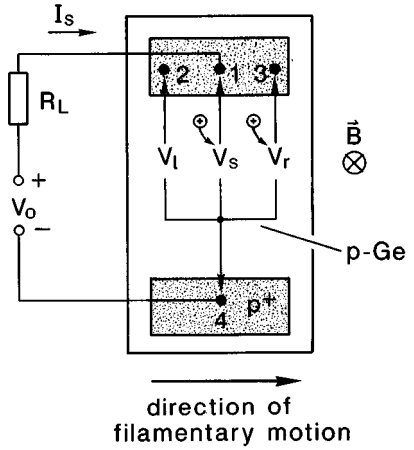

FIG. 1. The experimental setup used is similar to the one discussed elsewhere (Ref. 5), but instead of applying a constant voltage between the two planar contacts, the voltage is periodically switched on and off, in order to control the time of absence of a filament.

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noid sited around the sample. During the experiments, the sample was in direct contact with the liquid helium ($T=4.2$ K) and shielded against background irradiation.

The present experimental setup allows the simultaneous measurement of time traces resulting from different parts of the sample. That is, any spatial dynamics of current filaments can be disclosed. Specifically, comparison of the temporal order of extreme values observed in the signals of the total current I_s and the partial voltage drops V_l and V_r leads to the following interpretation: a current filament nucleates at one particular (say, the left) edge of the sample, then travels towards the opposite (say, the right) edge where it annihilates. Clearly, the motion of a filament across the sample directs to the positive pole of the Hall electric field.

One unsolved problem related with these findings concerns the nucleation site of the filaments. What kind of mechanism makes the sample edge located opposite to the annihilation site stand out compared to any other (e.g., the middle) part? There are two possibilities. First, the Hall electric field gives rise to an asymmetric field distribution. Second, the existence of any filament precursor can result in a preference for a distinct sample edge. The experiment discussed in the following indicates the strong influence of a preceding filament on the nucleation site of the subsequent one. Hereto, the above configuration was modified. Instead of applying a constant voltage bias, we have switched on and off periodically the voltage, where at the upper level filamentary motion takes place. The residence times of the lower and higher voltage levels are denoted by τ_{low} and τ_{high}, respectively. Upon variation of τ_{low}, we were able to control the minimum time of filament absence, e.g., to exert influence on the initial state for the nucleation of the next filament. τ_{high} is chosen to be larger than the time for the nucleation of the current filament.

Inspecting the three time traces of I_s, V_l, and V_r plotted in Fig. 2 enables one to determine the nucleation site of the first filament as a function of the residence time in the low-conducting state, τ_{low}. The correlation between the different signals provides criteria for the spatiotemporal development of a current filament during its existence. In what follows, we assume a traveling direction pointing from the left to the right. Nucleation at the left-hand side of the sample takes place when the corresponding local voltage trace V_r exhibits a minimum before the current I_s reaches its maximum [see Fig. 2(a)]. Nucleation in the middle part of the sample takes place when two conditions are fulfilled. First, the moment the voltage V_l drops to its minimum coincides with the moment the current I_s reaches its maximum. Second, the decrease of V_l is remarkably (by a factor of about 0.4) smaller than the value expected [see Fig. 2(b)]. Finally, nucleation at the right-hand side of the sample takes place when the minimum of the corresponding local voltage V_r coincides with the maximum of I_s [see Fig. 2(c)]. Note that in those cases where the first filament, which is generated after switching to the upper voltage level, nucleates in the middle or right part of the sample (i.e., the locations deviating from the ''natural'' nucleation site according to the dc voltage bias[5]), the successive one is generated immediately. That is, the recovery time elapsing between annihilation of the old and nucleation of the new filament[8] becomes relatively short. In any case, the new filament nucleates at the natural side of the sample. Whereas τ_{low} is an important parameter concerning the nucleation site, τ_{high} exerts no influence on the dynamics (provided τ_{high} admits development of the natural oscillation).

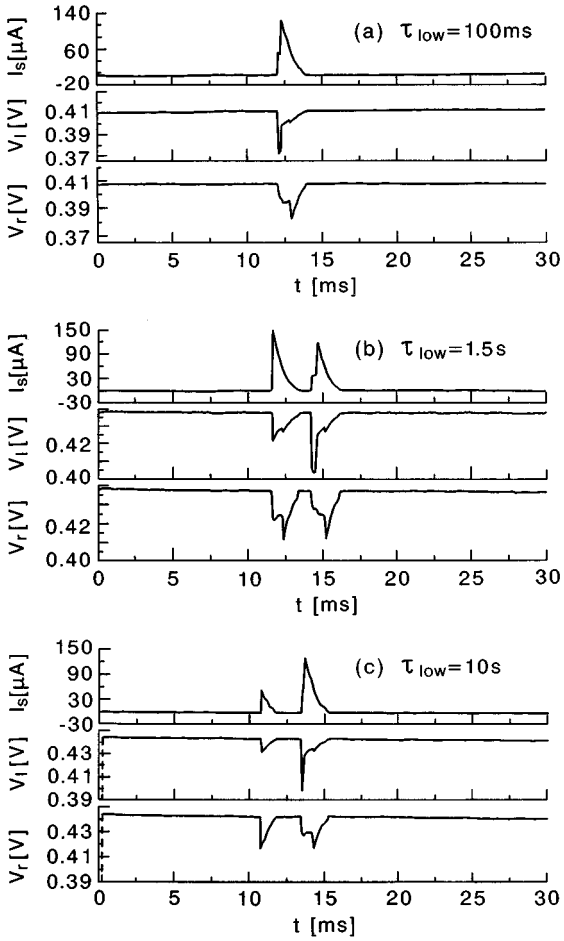

FIG. 2. Exemplary time traces of the sample current I_s and the two voltages V_l and V_r can be interpreted with respect to the spatial behavior of the filaments. The nucleation of the first filament after an externally controlled time τ_{low}, during which no filament existed, is explored. The time traces (a)–(c) belong to three different values of the residence times τ_{low} for the lower voltage level [(a) $\tau_{\mathrm{low}}=100$ ms, (b) $\tau_{low}=1.5$ s, and (c) $\tau_{\mathrm{low}}=10$ s] . The typical behavior of current and voltages changes in a characteristic way under elongation of τ_{low} (other parameters are $R_L=100\ \Omega$, $B=0.43$ mT, $V_0=0$ mV during τ_{low} and $V_0=410$ mV during τ_{high}).

The histograms in Fig. 3 show the probability of each nucleation site obtained from 200 switching events for three different values of τ_{low}. The arrow gives the direction of filamentary motion. Obviously, with increasing τ_{low} the maximum nucleation probability shifts to the same direction as that of filamentary motion. The characteristic distribution is narrow compared to our crude division of the sample into three distinct parts. There exists no time τ_{low} where we have nucleation in all three parts of the sample. We point out that the time scale for observing the total shift of the distribution spreads over several orders of magnitude. The sample shows some kind of a memory effect. That means the nucleation process ''senses'' the reminiscence of the previous filamentary state.

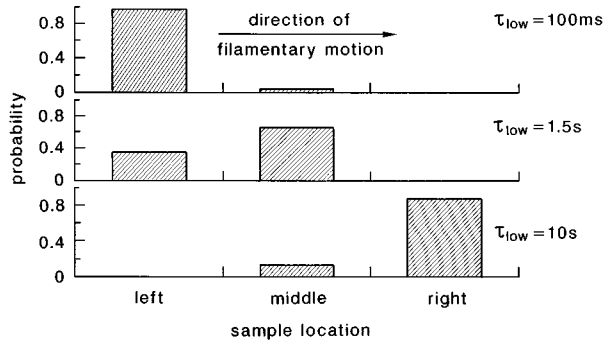

FIG. 3. The spatial probability distribution of nucleation is given for the same values of τ_{low} as the time traces in Fig. 2. The peak probability shifts to the same direction, as that of filamentary motion (other parameters as in Fig. 2).

One would expect that nucleation of a filament is most probable in that part of the sample where the electric field has a maximum. In an ideal geometry (i.e., with parallel contact edges), the maximum field develops between the contact probes 1 and 4 (see Fig. 1) in the middle part of the sample. However, in our experiment we observe an enhanced probability of filament nucleation on the right-hand side of the sample for large values of the time τ_{low}. Such unusual behavior can eventually be explained as a consequence of nonparallel contact edges, which give rise to a nonsymmetric distribution of the electrostatic potential. The existence of a higher electric field on the right-hand side of the sample enhances the nucleation probability there. This explanation finds support in an experiment carried out with reversed polarity of the magnetic field: the probability of nucleation of a filament in that preferred region never drops to zero, even for large values of τ_{low}.

In the following, the memory effect mentioned above is studied under additional illumination of the sample by visible light emitted by a light bulb. The bulb was located outside the glass cryostat. The incident light destroys the memory effect: nucleation of the first filament is always observed on the right part of the sample, as in the case where annihilation of the previous filament took place several seconds in advance ($\tau_{low} > 10$ s).

Obviously, the direction of the filamentary motion and the direction of the spatial change of the nucleation probability coincide (see Fig. 3). Impact ionization is most unlikely in those parts of the sample that are reminiscent of a previously existing current filament. A simple explanation connecting a reduced impact ionization rate with a filament reminiscence remains near at hand. If a depleted region is built up in tow of the traveling filament, a new filament is generated just at those sites where the sample at first recovers from depletion. In case the recovery process immediately starts after the filament has left, the region of its nucleation experiences the longest time of recovery. Thus, nucleation of a further filament takes place at the nucleation site of the previous filament. However, if we use different values of τ_{low} (see Fig. 2), recovery of the depletion can take place in a larger part of the sample, and the nucleation site is determined just by the distribution of the electric field.

III. SUMMARY

To conclude, we have demonstrated that the nucleation site of a current filament strongly depends on the history of the conducting state. Analysis of spatially resolved nucleation probabilities helps to entangle the dynamics that is determined by the lifetime and the sequence of the traveling filaments. In particular, nucleation is preferred in sample regions with the longest absence of a previous filament and inhibited in sample regions with latest presence of a filament. The memory capability turns out to extend over several seconds.

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