Different Types of Current Instabilities During Low-Temperature Avalanche Breakdown of p-Germanium

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Z. Naturforsch. **42 a,** 441 – 443 (1987); received January 27, 1987

The highly nonlinear current transport behavior of extrinsic germanium, electrically driven into distinct parameter regimes of impact-ionization-induced avalanche breakdown at liquid-helium temperatures, shows a variety of temporally unstable dissipative structures. We have observed experimentally three different types of current instabilities.

The examination of semiconductor instabilities provides a deeper understanding of the operation of practical semiconductor devices in nonlinear regimes. Quite recently, nonlinear oscillations and chaos were found in various current-carrying semiconductor systems [1–4]. In addition to the spontaneous oscillatory behavior in the electric post-breakdown region of p-germanium at low temperatures [1], this paper reports on different types of current instabilities observed experimentally in distinct ranges of control-parameter space during the onset of impurity-impact-ionization-induced avalanche breakdown.

Our experiments were performed on the same single-crystalline p-type germanium material as described in [1]. Having the typical dimensions of about $(0.2 \times 2 \times 5)\ \mathrm{mm}^3$ and an acceptor concentration of about $10^{14}\ \mathrm{cm}^{-3}$ (corresponding to a shallow impurity acceptor level of about 10 meV), the extrinsic germanium crystal carries properly arranged ohmic aluminum contacts evaporated on one of the two largest surfaces. An electric field was applied to the ohmic contacts (d.c. bias voltage V_0). A d.c. magnetic field B perpendicular to the broad sample surfaces could also be applied using a superconducting coil surrounding a copper metal shield employed for protection against external irradiation. The resulting electric current I was found from the voltage drop upon the load resistor (1 Ω or 100 Ω) connected in series to the semiconductor sample. During the experiments the sample configuration investigated was in direct contact with the liquid-helium bath kept at 4.2 K.

In extrinsic germanium cooled to liquid-helium temperatures, most charge carriers are frozen out at the impurities and the material becomes an electric insulator. Applying an electric field of sufficiently high strength (in the range of a few V/cm), impact ionization of the shallow impurities takes place in the bulk of the homogeneously doped semiconductor. The resulting avalanche breakdown persists until all impurities are ionized. The underlying nonequilibrium phase transition from a low conducting state to a high conducting state is directly reflected in strongly nonlinear regions of negative differential resistivity [1, 5]. Under proper variation of both the electric and the magnetic field (acting as control parameters) the resulting nonlinear current transport behavior displays a variety of temporally unstable dissipative structures, comprising the spontaneous formation of three different types of current oscillations described in the following.

First, relaxation oscillations attributed to the stochastical firing of individual avalanche breakdown bursts were found in the pre-breakdown regime at transverse magnetic fields of typically a few hundred Gauss. Corresponding to the initial rising part of the time-averaged current-voltage characteristic shown in Fig. 1, the time-resolved current profiles $I(t)$ traced in Fig. 2 reveal increasing firing density and magnitude of the breakdown bursts with increasing applied bias voltage V_0. Both the parameter dependence and the characteristic shape of such relaxation-type current instabilities suggest an oscillatory generation-recombination mechanism where the autocatalytic process of impurity impact ionization is dominated by the

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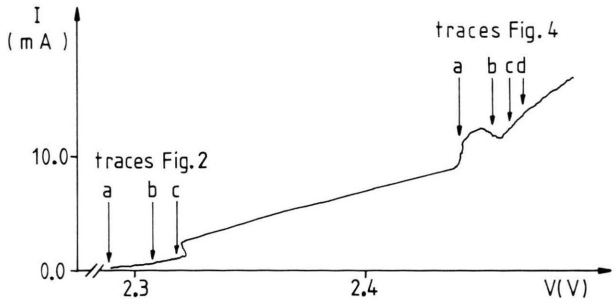

Fig. 1. Current-voltage characteristic obtained at the applied magnetic field $B = 200$ G (load resistor $R_L = 100\ \Omega$, bath temperature $T = 4.2$ K). Note that the bias voltage V_0 was applied to the series combination of the sample and the load resistor. The voltage V was measured along the sample.

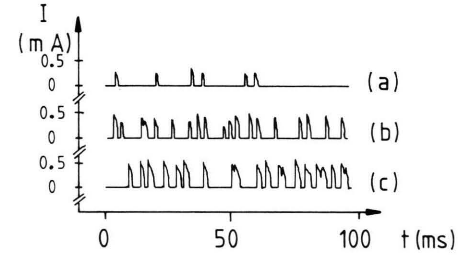

Fig. 2. Temporal current structures in the pre-breakdown regime obtained at different bias voltages (a) $V_0 = 2.280$ V, (b) $V_0 = 2.310$ V, (c) $V_0 = 2.320$ V (marked in Fig. 1) and the applied magnetic field $B = 200$ G (load resistor $R_L = 100\ \Omega$, bath temperature $T = 4.2$ K).

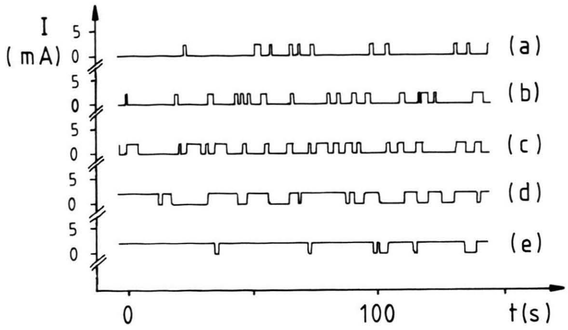

Fig. 3. Temporal current structures near the breakdown threshold obtained at different bias voltages (a) $V_0 = 2.378$ V, (b) $V_0 = 2.379$ V, (c) $V_0 = 2.380$ V, (d) $V_0 = 2.381$ V, (e) $V_0 = 2.382$ V and the applied magnetic field $B = 250$ G (load resistor $R_L = 1\ \Omega$, bath temperature $T = 4.2$ K).

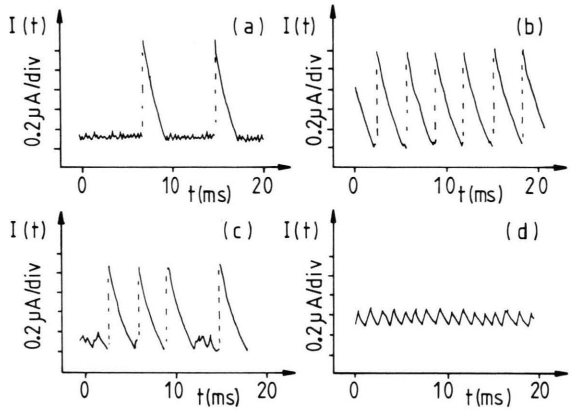

Fig. 4. Temporal current structures in the post-breakdown regime obtained at different bias voltages (a) $V_0 = 3.499$ V, (b) $V_0 = 3.505$ V, (c) $V_0 = 3.514$ V, (d) $V_0 = 3.542$ V (marked in Fig. 1 at the corresponding sample voltages (a) $V = 2.442$ V, (b) $V = 2.455$ V, (c) $V = 2.463$ V, (d) $V = 2.470$ V) and the applied magnetic field $B = 200$ G (load resistor $R_L = 100\ \Omega$, bath temperature $T = 4.2$ K).

competing recombination of the mobile charge carriers [6]. As a consequence of stability arguments, avalanche breakdown occurs sporadically on current pulses before reaching the stationary state of stable filamentary conduction in the post-breakdown regime.

Second, switching oscillations due to the stochastical switching of the electric current between two different conducting states were found in the parameter range near the breakdown threshold, where the S-shaped nonlinearity of the current-voltage characteristic just vanishes as a consequence of sufficiently high applied magnetic fields (corresponding to a just vanishing breakdown hysteresis at voltage-controlled operation). To get a vivid idea of the typical magnetic field dependence of the current-voltage characteristic, imagine the fold topology of a cusp catastrophe [7]. The bifurcation point at the cusp of beginning biomodality exactly localizes the critical breakdown threshold for sudden emergence of spontaneous switching oscillations. Accordingly, Fig. 3 displays distinct time-resolved current structures $I(t)$ of highly rectangular pulses of constant amplitude. Under slight increase of the impressed bias voltage V_0 and fixed magnetic field $B = 250$ G, the stochastically occurring current pulses show increasing width and density. Note the very slow time scale of these switching oscillations during the gradual transition to continuous current flow. Such a characteristic type of current instability may be interpreted as the stochastic formation of locally limited breakdown microplasmas [8].

Third and finally, spontaneous current oscillations superimposed upon the steady d.c. current were found in the strongly nonlinear post-breakdown regime of negative differential resistivity. Corresponding to the N-shaped curvature of the current-voltage characteristic shown in Fig. 1, the time-resolved current structures $I(t)$ traced in Fig. 4 again display relaxation-type oscillatory behavior at ms time scale. However, the pulse amplitudes are relatively small compared to the total current flow of typically a few mA. Beyond the parameter dependence presented in Fig. 4, the temporal current behavior in the post-breakdown region changes dramatically under slight variation of appropriate control parameters (electric field, magnetic field, temperature), exhibiting the typical universal scenarios of chaotic nonlinear systems [1]. The observed dynamical phenomena can be explained in terms of a novel nonlinear transport model involving impact ionization of impurity levels coupled with either dielectric relaxation of the electric field or energy relaxation of the hot carriers [9]. Taking further into account experimental evidence of the filamentary conduction mechanism in the post-breakdown regime together with the spatial identification of temporal dissipative structures as localized carrier density oscillations in the filament wall [10], the idea of "breathing" current filaments originates from the possible interaction between longitudinal relaxation instabilities and transverse filamentary instabilities [9].

The authors acknowledge financial support of the Stiftung Volkswagenwerk and helpful discussions with R. Kassing, K. M. Mayer, U. Rau, B. Röhricht, and E. Schöll.

[1] J. Peinke, A. Mühlbach, R. P. Huebener, and J. Parisi, Phys. Lett. **108A,** 407 (1985); – J. Peinke, B. Röhricht, A. Mühlbach, J. Parisi, Ch. Nöldeke, R. P. Huebener, and O. E. Rössler, Z. Naturforsch. **40a,** 562 (1985); B. Röhricht, B. Wessely, J. Peinke, A. Mühlbach, J. Parisi, and R. P. Huebener, Physica **134 B,** 281 (1985).

[2] S. W. Teitsworth, R. M. Westervelt, and E. E. Haller, Phys. Rev. Lett. **51,** 825 (1983); – S. W. Teitsworth and R. M. Westervelt, Phys. Rev. Lett. **56,** 516 (1986); – E. G. Gwinn and R. M. Westervelt, Phys. Rev. Lett. **57,** 1060 (1986).

[3] G. A. Held, C. Jeffries, and E. E. Haller, Phys. Rev. Lett. **52,** 1037 (1984); – G. A. Held and C. Jeffries, Phys. Rev. Lett. **55,** 887 (1985); – G. A. Held and C. Jeffries, Phys. Rev. Lett. **56,** 1183 (1986).

[4] K. Aoki, T. Kobayashi, and K. Yamamoto, J. Phys. Soc. Japan **51,** 2373 (1982); – K. Aoki and K. Yamamoto, Phys. Lett. **98 A,** 72 (1983); – K. Aoki, O. Ikezawa, N. Mugibayashi, and K. Yamamoto, Physica **134 B,** 288 (1985).

[5] E. Schöll, in "Festkörperprobleme", Vol. 26, ed. P. Grosse, Vieweg, Braunschweig 1986, p. 309; – E. Schöll, Nonequilibrium Phase Transitions in Semiconductors (Springer Series in Synergetics, Berlin, to be published 1987).

[6] W. Schultz, in "Festkörperprobleme", Vol. 5, ed. F. Sauter, Vieweg, Braunschweig 1965, p. 165.

[7] E. C. Zeeman, Catastrophe Theory, Addison-Wesley, London 1977.

[8] W. Mönch, in "Festkörperprobleme", Vol. 9, ed. O. Madelung, Vieweg, Braunschweig 1969, p. 172.

[9] E. Schöll, Physica **134 B,** 271 (1985); – E. Schöll, Phys. Rev. B **34,** 1395 (1986); – E. Schöll, J. Parisi, B. Röhricht, J. Peinke, and R. P. Huebener, Phys. Lett. **119 A,** 419 (1987).

[10] J. Mannhart, R. P. Huebener, J. Parisi, and J. Peinke, Solid State Commun. **58,** 323 (1986); – K. M. Mayer, R. Gross, J. Parisi, J. Peinke, and R. P. Huebener, Solid State Commun. (to be published).