with $a = 10^{-3}$ cm, $b = 0.5$ cm, $n = 380$, and $a = 10^{-3}$ cm, $b = 0.12$ cm, $n = 930$. (The symbols in Fig. 2a are: × - $\theta_1 = 7.3 \times 10^{-4}$, $\theta_2 = 6.7 \times 10^{-3}$; ● - $\theta_1 = 3.5 \times 10^{-4}$, $\theta_2 = 3.3 \times 10^{-3}$; o - $\theta_1 = 2.6 \times 10^{-4}$, $\theta_2 = 2.5 \times 10^{-3}$; in Fig. 2b: ● - $\theta_1 = 2.6 \times 10^{-4}$, $\theta_2 = 2.5 \times 10^{-3}$; $a = 4 \times 10^{-3}$ cm, $b = 5 \times 10^{-1}$ cm, $n = 380$; × - $\theta_1 = 2.6 \times 10^{-4}$, $\theta_2 = 2.5 \times 10^{-3}$, $a = 10^{-3}$ cm, $b = 1.25 \times 10^{-1}$ cm, $n = 930$).

In all cases, the radiation was registered in the energy region $\hbar\omega \gtrsim 15$ keV. We note that the electron registration efficiency is larger by 2 - 3 times in the case of a layered medium with n = 930 layers than in the case of a medium with 380 layers, owing to the increased number of layers and the decreasing plate thickness (i.e., the decreased absorption).

It follows from these preliminary results, as expected, that the electron registration efficiency has a sharp dependence on the energy. In the investigated angle and energy intervals, the efficiency reaches $\varepsilon \simeq 0.1$.

Recognizing that the transition-radiation spectrum decreases rapidly with increasing $h\omega$, it is obvious that the use of γ-quantum detectors capable of recording γ quanta with energies lower than used in our case will make it possible to register high-energy particles with $\varepsilon \simeq 1.0$, provided the values of θ_1 and θ_2 and the number of layers are suitably chosen. Since the intensity of the transition radiation depends on γ, it is also obvious that such a detector can be used to identify particles with different masses at high resolution in the momentum region $\gtrsim 100$ GeV/c, a rather complicated task if Cerenkov counters are used.

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S-SHAPED CURRENT-VOLTAGE CHARACTERISTIC AND PINCHING OF CURRENT IN GUNN DIODES

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In highly doped Gunn diodes, the field in the domain becomes strong, so that band-band breakdown takes place, and electron-hole pairs are generated as a result. This leads to current-controlled negative resistance (S-shaped characteristic) [1 - 3], the mechanism of which is not yet clear, and also to the appearance of stimulated emission and to the formation of glowing filaments [4]. These phenomena were observed in GaAs [4], InP [5], CdTe [6], and in other compounds.

The present paper is devoted to an explanation of the mechanism of occurrence of S-shaped characteristics of Gunn diodes and the ensuing pinching of the current.

An important factor in the understanding of the mechanism of formation of S-shaped characteristics is that the recombination takes place within a time much longer than the domain transit time. The maximum field in a domain in a highly-doped sample depends on the electron density averaged over the sample in the following manner [7]:

$$E_m = An^{1/4}(E - E_R)^{1/2}, \tag{1}$$

where E is the field applied to the sample, E_R is the field outside the domain, n is the conduction electron density, and A is a proportionality coefficient that depends on the parameters of the V(E) curve, on the average electron drift velocity, on the diffusion coefficient, on the dielectric constant, and on the sample length. Since impact ionization occurs only in the strong-field domain, the generation rate g averaged over the transit time can be written in the form [8]:

$$g = g_\infty \exp\left(-\frac{E_0^2}{E_m^2}\right). \tag{2}$$

It is seen from (2) that owing to the dependence of E_m on n, as given in (1), g depends on the pair concentration[1]. This makes possible a multiply-valued dependence of the electron density, and consequently also of the current, on the voltage applied to the sample. Different values of the current correspond to different field amplitudes in the domain. The S-shaped current-voltage characteristic of a homogeneous sample leads to pinching of the current.

We consider a sample in the form of a thin plate. We direct the z axis along the external electric field, the x axis along the plate thickness. In this case, all the quantities depend only on x and on the time t. The equations describing the Gunn diode, in a time scale large compared with the domain transit time, can be written in the form

$$j_p = -eD_p\left(1 + \frac{p}{n_0 + p}\right)\frac{\partial p}{\partial x}, \tag{3}$$

$$\frac{\partial p}{\partial T} + \frac{1}{e}\frac{\partial j_p}{\partial x} = g(n_0 + p) - Rp(n_0 + p) - \frac{p}{\tau}. \tag{4}$$

Here j_p is the density of the hole current in the x direction, p is the pair concentration, n_0 the equilibrium electron concentration ($n = n_0 + p$), D_p the hole diffusion coefficient, τ the linear-recombination time constant, and R the coefficient of quadratic recombination. Equation (3) describes ambipolar diffusion of electrons and holes in the x direction. (In the derivation of (3) it was assumed that $D_p/D_n = \mu_p/\mu_n$ and $\mu_p \ll \mu_n$, when μ_p and μ_n are the hole and electron mobilities.) Equation (4) is the balance equation of the electron-hole pairs.

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[1] It should be noted that the qualitative results that will be obtained here do not depend on the concrete form of the function $g(E_m)$; all that matters for the qualitative picture is the exponential dependence of g on n.

The current-voltage characteristic of a homogeneous sample is determined by the zero of the right side of Eq. (4). We introduce the following dimensionless quantities: $N = R/g_\infty$ is the dimensionless pair concentration, $N_0 = n_0R/g_\infty$ the dimensionless electron concentration, $\tau = (g_\infty\tau)^{-1}$ the reciprocal dimensionless linear-recombination time, and $\mathcal{E} = (A^2/E_0^2)\,(E - E_R)\,\sqrt{g_\infty/R}$ the dimensionless difference between the field applied to the sample and the field outside the domain. Then the right side of (4) can be written in the form:

$$f(N) \equiv (N + N_0)\exp[-1/\mathcal{E}\sqrt{N + N_0}] - N(N + N_0) - rN = 0. \tag{5}$$

From (5) we have:

$$\mathcal{E} = \frac{1}{\sqrt{N + N_0}\,\ln\dfrac{N + N_0}{N(N + r + N_0)}} . \tag{6}$$

Equation (6) is the dimensionless current-voltage characteristic of the homogeneous sample: in strongly doped samples the average drift velocity of the carriers is practically independent of the applied voltage in the presence of a strong-field domain [7]. Therefore the current depends on the field in the same manner as N.

The characteristic $N(\mathcal{E})$ is triply-valued in a definite range of fields and concentrations. The upper value of the concentration at which the S-shaped characteristic vanishes is $n_0 = g_\infty/2R\,\exp(3)$, which amounts to $\sim 10^{19}$ cm^{-3} for GaAs. The threshold field E_{cr} at which the section with the negative differential conductivity (NDC) begins increases with increasing parameter N_0. E_{cr} may turn out to lie in the region of fields that are not attainable experimentally if n_0 is small enough. This result agrees qualitatively with the experimental data [9]. It must also bE noted that a change takes place in the $E_m(n_0, E)$ dependence at small values of n_0 [7]. The qualitative results, however, remain the same when the concrete form of the $E_m(n_0, E)$ is changed.

Let us consider a sample under conditions corresponding to a section with NDC. Assume that fluctuations have caused the concentration of the non-equilibrium carriers to increase in some region of the cross section. In this region, the pair generation rate increases exponentially. On the section with the NDC, this increase exceeds the corresponding increase of the recombination. The fluctuation becomes more intense. At large concentrations, its growth is limited by diffusion, giving rise to a stationary pinch (layer) of strong current, i.e., a pinch (layer) with increased carrier density. The pinch is flat if the sample is a thin plate. Such a pinch configuration can explain the location of the glowing filaments along the axis of the sample, observed in [4]. These filaments were disposed over a layer with increased carrier density, which is produced when the pinch is formed.

The instability is absolute, and the strong-current pinch is stationary. Integrating the system of equations (3) and (4), we can find the connection between the pair concentration N_{min} outside the pinch and the maximum pair concentration N_{max} inside the pinch:

$$\int_{N_{min}}^{N_{max}} f(N)\left(1 + \frac{N}{N + N_0}\right) dN = 0 . \tag{7}$$

Equation (7) is analogous to the area rule in the theory of strong-field domains [10]. It follows from (7) that with increasing E the maximum pair concentration in the pinch decreases. The pinch dimension is proportional to the "generation-diffusion length" $(D_p g_\infty^{-1})^{1/2}$ and increases with increasing E. An investigation of the system (3) - (4) with allowance for (7) also shows that the excitation of the pinch is hard and that hysteresis exists between the threshold currents at which the pinch appears and disappears.

Interesting phenomena should occur when the sample with the pinch is placed in an external magnetic field H perpendicular to the plane of the pinch. The instability then changes from absolute to convective. The pinch begins to drift towards the wall of the sample, with a velocity V_H on the order of $\mu_n \mu_p EH/c$. The physical mechanism of the pinch motion is as follows: the holes, which are much heavier and less mobile than the electrons, move in the Hall field of the electrons (just as in the Suhl effect). They are followed by the electrons, in order to maintain the electric neutrality. If the rate V_S of the surface recombination is small compared with V_H, the pinch stops at the wall of the sample. When $V_S > V_H$, the pinch vanishes at the wall, after which a new pinch is produced at the center of the sample and the cycle is repeated. In this case, voltage oscillations should be observed in the external circuit, at frequencies on the order of V_H/a (a - transverse dimensions of the sample); these frequencies are much lower than the Gunn generation frequency.

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ANOMALOUS THERMOELECTRIC POWER OF FERROMAGNETIC METALS WITH MAGNETIC IMPURITIES

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Scattering of electrons by magnetic impurities in ferromagnetic metals, together with scattering by magnons, can lead to an anomalously large thermoelectric power, commensurate with k/e. The cause of this fact can be qualitatively explained as follows. An electron with a spin in the same (opposite) direction as the magnetic moment ↑(↓) can only absorb (emit) a magnon. Therefore, as a result of the single-magnon process, an electron with spin ↑(↓) and with energy ε higher (lower) than the Fermi level ε_F can go over into the region above (below) the Fermi surface, and by the same token change the direction of the drift under the incluence of the temperature gradient, whereas an electron with spin ↑(↓) and energy higher (lower) than ε_F does not change its drift direction in the single-magnon process; in other words, the effective relaxation time of electrons with a given spin is not an even function of $\varepsilon - \varepsilon_F$. Thus, each of the groups of electrons with spin ↑ and ↓ makes a contribution