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DYNAMIC NEGATIVE DIFFERENTIAL CONDUCTIVITY (NDC) IN HOMOGENEOUS AND ELECTRICALLY-STABLE SEMICONDUCTORS

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A homogeneous semiconductor can have a negative differential conductivity (NDC) at a nonzero frequency, and nevertheless remain stable against arbitrary fluctuations.

The existence of NDC in inhomogeneous semiconductors that are stable against electric fluctuations is a well known and long established fact. Examples are tunnel diodes, impact avalanche and transit time diodes, and others. It is also known that in homogeneous semiconductors the presence of static NDC leads to a growth of sufficiently long-wave fluctuations and, in final analysis, to the breakdown of the sample into domains. We wish to call attention to the fact that dynamic DNC can occur in homogeneous semiconductors in a certain frequency band ω in the absence of static NDC owing to the dispersion of the differential conductivity $\sigma_d(\omega)$, i.e., we can have in the frequency interval $0 < \omega_1 \leq \omega \leq \omega_2 < \infty$ at $\sigma_d(0) > 0$

$$\mathrm{Re}\,\sigma_d(\omega) < 0, \tag{1}$$

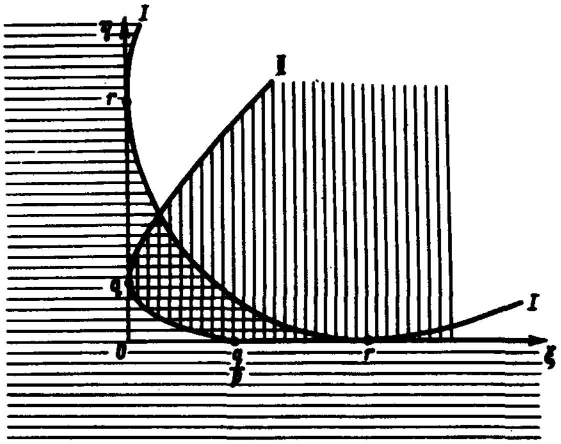
and in spite of (1), the semiconductor remains stable against fluctuations at all frequencies and at all wavelengths.

This possibility was corroborated by us in detail, using as an example a homogeneous monopolar semiconductor having traps of two types, 1 and 2, and having capture coefficients $C_{1,2}(E)$ that depend on the electric field intensity and having ejection probabilities $g_{1,2}(E)$. We solved the standard linearized system of equations of the recombination kinetics, as well as the Poisson and continuity equations, and calculated the differential conductivity $\sigma_d(\omega, K) = \delta j/\delta E$ with account taken of the temporal and spatial dispersion (δj and δE are the variations of the current density j and of the field E, respectively, at the frequency ω and wave number K). In the simplest case of ohmic contacts on the boundaries $X = 0$ and $X = L$, an alternating electric signal of frequency ω applied to the sample excites in the interior of the sample only homogeneous oscillations with wave number $K = 0$. Then the impedance is $Z(\omega) = L\sigma_d^{-1}(\omega, K = 0) \equiv L\sigma_d^{-1}(\omega)$, and the condition (1) is equivalent to $\mathrm{Re}Z(\omega) < 0$. In other words, the current and the voltage of frequency ω are shifted in phase by an angle larger than $\pi/2$, i.e., a power gain is obtained on the average over the period of the oscillations. When such a sample is connected to a tank circuit tuned to the frequency ω, self-excitation of oscillations can take place. Of course, to realize this possibility the semiconductor must remain stable against fluctuations and, for example, not break up into domains.

To check on the stability of the fluctuations, we solved the dispersion equation

$$\sigma_d(\omega, K) = 0 \tag{2}$$

with respect to ω for arbitrary real values of K. We sought semiconductor parameters such that (a) the condition (1) could be satisfied at any real frequency ω and (b) the imaginary part $\mathrm{Im}\omega$ of the complex roots of Eq. (2), for any real K, had a sign corresponding to damping of the fluctuations with time. It is convenient to represent the results of such an analysis in the plane of the variables ξ and η (see the figure), where



$$\xi = \frac{[\tau_1^{-1}\sigma_{d1}(0) + \tau_2^{-1}\sigma_{d2}(0)]}{en_0\mu(\tau_1^{-1} + \tau_2^{-1})}, \qquad \eta = \frac{\sigma_d(0)}{en_0\mu}\tau. \tag{3}$$

In Eq. (3), e is the electron charge, n_0 is the stationary concentration of the free electrons, μ is their mobility and is assumed to be independent of E, and $\sigma_{d1}^{(0)}$ is the partial static differential conductivity, defined under the condition that the semiconductor contains only traps of the first type. The quantity $\sigma_{d2}(0)$ is analogously defined. The total static differential conductivity is $\sigma_d(0) \equiv \sigma_d(\omega = 0)$. The reciprocal recombination times are $\tau_{1,2}^{-1} = \tau_{r1,2}^{-1} + \tau_{g1,2}^{-1}$, where $\tau_{r1,2}^{-1} = C_{1,2}(E_0)(N_{1,2} - N_{1,2}^-)$ are the times of capture from the traps of the first and second type ($N_{1,2}$ are the concentrations of these traps, $N_{1,2}^-$ are the equilibrium concentrations of the bound electrons), and $\tau_{g1,2}^{-1} = [g_{1,2}(E_0) + C_{1,2}(E_0)n_0]$ are the ejection times (E_0 is the stationary value of the field E). The parameters are given by

$$p = \frac{(\tau_{g1}^{-1} + \tau_{g2}^{-1})}{(\tau_1^{-1} + \tau_2^{-1})} > 0, \quad q = \frac{(\tau_{g1}\tau_{g2})^{-1}}{(\tau_1^{-1} + \tau_2^{-1})^2} > 0,$$

$$r = \frac{[(\tau_{g1}\tau_{g2})^{-1} + (\tau_{g1}\tau_{r2})^{-1} + (\tau_{g2}\tau_{r1})^{-1}]}{(\tau_1^{-1} + \tau_2^{-1})^2} > 0. \tag{4}$$

It follows from the definitions (4) that

$$p^2 \geqslant 4q, \qquad r \geqslant q, \qquad r \geqslant \frac{q}{p}. \tag{5}$$

The curves in the figure were plotted under the simplifying assumptions $\tau_M \ll \tau_{1,2}$, $Dk \ll \mu E_0$, $D/(\mu E_0)^2\tau_M \ll 1$, where τ_M is the Maxwellian relaxation time and D is the diffusion coefficient. The last reinforced inequalities are equivalent to neglecting the diffusion current. The diffusion cannot exert any influence on condition (1), which is formulated at K = 0. As to the stability conditions, the diffusion can only facilitate the satisfaction of these conditions. It is assumed, in addition, that the thermoelectric current of the hot electrons does not exceed the diffusion current. The condition for this is $D/(\mu E_0)^2\tau_e > 1$, where τ_e is the energy relaxation time.

The equation of parabola I in the figure is

$$(\eta - \xi + r)^2 - 4r\eta = 0, \qquad (6)$$

and the equation of parabola II is

$$(\eta - q)^2 - 2p\xi(\eta + q) + p^2\xi^2 = 0. \qquad (7)$$

Parabolas I and II lie entirely in the upper right quadrant. Parabola I is tangent to the axes η and ξ at the points ($\eta = r$, $\xi = 0$) and ($\eta = 0$, $\xi = r$), respectively, while parabola II is tangent to the same axes at the points ($\eta = q$, $\xi = 0$) and ($\eta = 0$, $\xi = q/p$). The relative placement of these parabols in the figure takes into account the inequalities (5). The dynamic NDC can exist only at those points of the (ξ, η) plane lying outside parabola I, which is the region shaded horizontally. The stability at all values of the wave number K is ensured only for points inside the region bounded by parabola II and by the ξ-axis segment to the right of the point $\xi = q/p$ — the vertically-shaded region. It is seen from the figure that these two regions always overlap. Consequently, there is always a region in the (ξ, η) plane where the possibility of dynamic DNC combines with stability of the semiconductor against arbitrary fluctuations. This section is doubly hatched in the figure. We can conclude from definitions (3) and (4) and from the figure that the doubly-hatched region is broader, meaning that experimental observation of the effect is easier if the parameter q is not too small in comparison with the parameter r. This can be attained in practice by decreasing to a minimum the ejection times τ_{g1} and τ_{g2} by using suitable additional illumination. In addition, to obtain the effect it is necessary to have traps that lead to a sublinear static current-voltage characteristic ($\sigma_d(0) < en_0\mu$).

We have also calculated the impedance $Z(\omega)$ of a semiconductor with two types of traps, but with antibarrier contacts on the end. It turned out that even with such contacts it is possible to obtain simultaneously both $\mathrm{Re}Z(\omega) < 0$ and stability against fluctuations. We considered also another system, namely a semiconductor with inertially heated electrons and with impurities under conditions close to breakdown. For this system we were also able to confirm the feasibility of dynamic NDC in conjunction with fluctuation stability. We emphasize that this effect vanishes if traps of one type are removed in our first example, and if in our second example we remove the impurity or make the heating instantaneous. Thus, we are dealing with an effect typical of systems in which the relaxation to equilibrium is described not by one but by at least two different times. In our examples these were either different recombination times at the two types of traps, or an energy relaxation time different from the breakdown time.

The feasibility of dynamic NDC in homogeneous semiconductors was investigated in [1]. However, the dynamic NDC mechanism which we examined in detail for monopolar semiconductors with traps of two types was not discussed in [1]. In addition, and this is the crux of the matter, in our article we indicate, apparently for the first time, that dynamic NDC is possible in semiconductors that are stable against fluctuations.

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GROWTH OF TOTAL CROSS SECTIONS AND ELASTIC SCATTERING

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A simple expression is proposed for the amplitude of elastic proton-proton scattering; this expression corresponds to the Froissart growth of the total cross section and describes satisfactorily all the differential cross section data obtained with the CERN storage rings.

Measurements at CERN have shown [1] that the total cross section of proton-proton scattering increases rapidly with energy. At the same time, the slope parameter of the diffraction peak and the ratio of the elastic cross section to the total cross section vary slowly with