Terahertz-range oscillations of the ballistic current of electrons with a negative effective mass

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Ballistic diodes with a doped base of optimum length generate electrical oscillations in the range 2.5–4.0 Hz. The oscillation frequency is an internal parameter of the electron gas in the diode. It can be tuned continuously by varying the voltage across the diode. The generation itself and also the resonant properties of the structure are clearly governed by the particular dispersion relation for the electron energy, which contains a region with a negative effective mass. © *1995 American Institute of Physics.*

We have studied a new mechanism for the excitation of electrical oscillations in the terahertz range. The mechanism is based on the particular dispersion relation for the energies of the electrons (or holes) which cross the thin doped base of a ballistic n^+nn^+ (or p^+pp^+) diode. The distinctive feature of the dispersion relation $\epsilon(\mathbf{p})$, where $\mathbf{p}$ is the quasimomentum, is the existence of an interval of p_x values (the x axis is chosen to run along the direction of the electron current) in which there is a negative effective mass. Figure 1 shows an $\epsilon(p_x)$ curve with a negative-mass region of this type. Previous papers[1–4] by our group have described methods for arranging the necessary $\epsilon(\mathbf{p})$ curves (for 3D and 2D electron gases) and also some unconventional steady-state distributions of the electron density $n(x)$ and the electric potential in the case of the ballistic transport of such electrons. These distributions are distinguished by the presence of two dipole space-charge regions (not just one!) in a certain interval of the voltage across the structure. One of these regions (the usual one) is near the cathode, while the other one (the unusual one) forms near the anode. The space between these two space-charge regions is filled with a quasineutral layer (a column) in which the positive charge of the donors is neutralized by the negative charge of exclusively the drifting electrons with a negative effective mass. The presence of a layer of substantial size with drifting negative-effective-mass electrons indicates that such steady-state distributions are probably unstable, since in an unbounded electron plasma of this type any longitudinal oscillations are convectively unstable, with a growth rate equal to the plasma frequency determined by the negative mass.[2]

In the present letter we demonstrate the following: 1) Beginning at certain thickness l_c of the n-type base, and in a certain range of the voltage on this base, steady-state distributions of the density and the potential are indeed unstable. 2) At a given voltage under short-circuit conditions (or during ohmic loading), a regime of steady-state oscillations of the ballistic current arises against the background of a steady-state component. The oscillations are approximately sinusoidal. 3) Their frequency is not determined in any way by the external resonator (the circuit); it is a property of the drifting electrons in

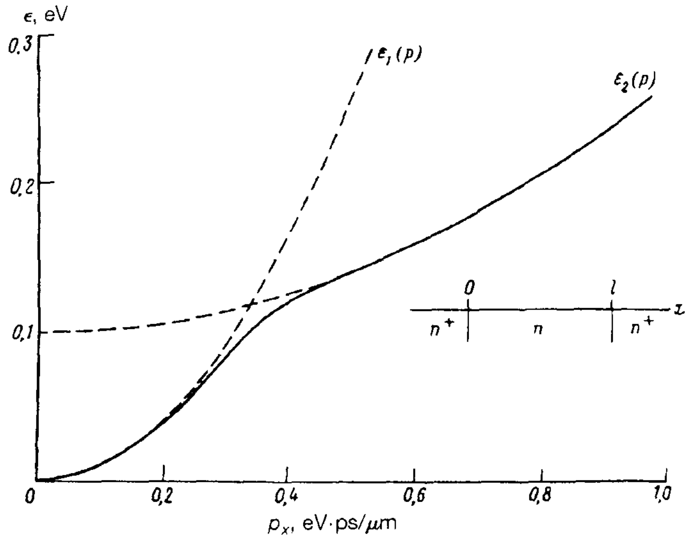

FIG. 1. The dispersion relation $\epsilon(p)$ with a region of a negative effective mass as plotted from Eq. (1). $m=0.085m_0$, $M=6$ m, $\epsilon_0=0.1$ eV, $\Delta=0.02$ eV. The inset shows the n^+nn^+ structure.

the base of the diode. Within certain limits, it depends on the length of the base and on the base voltage. These results, along with some others presented below, were established through direct numerical integration of a system of equations incorporating a spatially 1D Poisson equation and a spatially 1D, time-varying, collisionless kinetic equation for electrons with an isotropic dispersion relation

$$\epsilon(\mathbf{p})=\tfrac{1}{2}(\epsilon_1(p)+\epsilon_2(p)-\{[\epsilon_1(p)-\epsilon_2(p)]^2+4\Delta^2\}^{1/2}). \tag{1}$$

Here $p=|\mathbf{p}|$; $\epsilon_1(p)=p^2/2m$; $\epsilon_2(p)=\epsilon_0+p^2/2M$; $M>2m$; and $\epsilon_0\gg\Delta$. In the numerical procedure whose results are described below we assumed $M/m=6$ or 3, $m=0.042m_0$ or $0.085m_0$ (m_0 is the mass of a free electron), $\epsilon_0=0.1$ or 0.2 eV, and $\Delta=0.002$ or 0.02 eV. The thickness of the n-type base in the structure was varied over the interval from 0.1 to 0.2 μm. The concentration of dopant donors in the base was taken to be $n_0=5\times10^{17}$ cm^{-3}, the dielectric constant was taken to be $\kappa=12.9$, and the temperature of the medium was taken to be $T=300$ K. In the absence of a current, the electrons were assumed to have an equilibrium Fermi–Dirac distribution. We took this to be the distribution of the electrons entering the n-type base from the side of the n^+ cathode and from the side of the n^+ anode. The Fermi energy for these and the others was assumed to have the same value (we assumed a symmetric structure)—the value corresponding to equilibrium electron densities $n(0)=n(l)=5\times10^{18}$ cm^{-3} at the n^+ contacts (in the absence of a current). These distributions of the incident electrons served as boundary conditions for the kinetic equation. When there was an external voltage U on the base, the difference between the Fermi energies of the electrons entering from the two sides was eU. The distributions of the potential and the density were found by a self-consistent space-time procedure involving the splitting scheme described in Ref. 5 (no simplifications were made in the system of equations to be solved). Calculations were carried out both for a given voltage U on the anode (i.e., under short-circuit conditions) and for a fixed ohmic load in the external circuit.

Two procedures were used to calculate the current. In the first, some initial (not necessarily equilibrium) distribution of the potential in the electrons was specified, and the time evolution of this distribution after the imposition of a voltage U on the anode was studied. Outside the current saturation region[2-4] on the steady-state current–voltage characteristic, this evolution terminates at a certain current value $J=J(U)$ corresponding to the steady-state characteristic.[4] Far from the saturation region, the relaxation process $J(t)$ is aperiodic, and quickly comes to a halt. Near the nominal boundaries of this region, the relaxation is oscillatory. It lasts longer, the closer the voltage U is to these boundaries. Specifically, at an oscillation period of 0.3–0.4 ps the decay time is many picoseconds.

Within the voltage interval defined by the nominal boundaries, the relaxation does not end in a steady-state value; there is instead a transition to periodic oscillations of the current with a stable period and a stable amplitude. For all the parameters of the sample and all voltages considered, these steady-state current oscillations are approximately sinusoidal, and their amplitudes are small in comparison with the average current ($<6\%$).

The purpose of the second current-calculation procedure was to "measure" the U dependence of the amplitude and period of the steady-state oscillations. For this purpose we specified the voltage U to be of the form $U(t)=U_0+U't$, where the voltage rise rate U' was taken to be small (so that the increase in U over one oscillation period would be insignificant at a qualitative level). The initial voltage U_0 was chosen well below the lower boundary of the oscillation interval. Figure 2 shows curves of $J(t)$ found for this specification of $U(t)$, for samples with six base lengths l (0.13, 0.135, 0.14, 0.15, 0.175, and 0.2 μm), for otherwise equal parameter values (which are specified in the Fig. 2 caption). Outside the oscillation interval, the curve of $J(t)$ gives us a quasisteady current–voltage characteristic of the structure, as measured by the computer-controlled characteristic plotter. Inside this interval we find oscillations whose amplitude and period vary progressively with increasing U. The changes in the amplitude initially reduce to a smooth increase in the amplitude with U, then to the attainment of a certain range of U with a maximum amplitude, and then to a smooth decay to zero. Small undamped oscillations are detected even at $l=0.125$ μm. A further increase in l to 0.15 μm leads to both an increase in the maximum oscillation amplitude and an expansion of the voltage range in which the oscillations exist. A further increase in l causes a further expansion of the U range, but now without any visible increase in the maximum amplitude. The voltage at which the amplitude reaches its maximum tends to increase with increasing l. The trends in the changes in the frequency are far more definite: 1) At a given length l, the frequency clearly increases with increasing U. In particular, at $l=0.175$ and 0.2 μm, the frequency increases by a factor of at least 1.5 as U varies from the beginning to the end of the oscillation region (from $f=2.5$ to 3.75 THz). 2) With increasing l, the frequency undergoes a quite definite decrease (at $U=0.2$ V, from $f=4$ THz and $l=0.13$ μm to $f=2.5$ THz at $l=0.2$ μm).

An ohmic external load, varied over a fairly broad range, does not change the general picture: An increase in the external resistance R from 0 (short-circuit conditions)

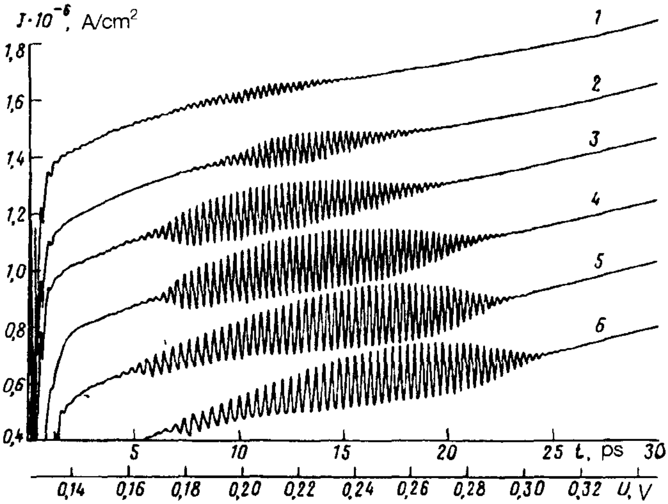

FIG. 2. Time evolution of the total current density $J(t)$ for diodes with various base lengths l, for a voltage with a time evolution $U(t)=U_0+U't$, where $U_0=0.125$ V and $U'=7.4$ mV/ps. The shift between the origins of the current scale for two adjacent curves is 0.2×10^6 A/cm^2. 1—$l=0.13$ μm; 2—0.135; 3—0.14; 4—0.15; 5—0.175; 6—0.2 μm. The parameter values of the structure are the same as in Fig. 1. Shown along with the scale of the real time along the abscissa is a voltage scale corresponding to the assumed time evolution $U(t)$.

to 4×10^{-7} Ω/cm^2 (with preservation of the working point) leads to a natural decrease in the current oscillation amplitude by a factor $\simeq1.5$. The efficiency of the oscillation generator obtained under these conditions is estimated to be above 0.5%.

Corresponding to the oscillations in the electric current are oscillations in the density of drifting electrons in the central part of the base of the diode. Figure 3 shows six snapshots of the electron distribution in the quasineutral column and at its boundaries, taken at uniform time intervals during one oscillation period. The region under consideration here has room for one or two maxima of the density, which are traveling away from the cathode toward the anode, with changes in amplitude. The changes in the density are small everywhere.

Variations of the parameter Δ (under the condition $\Delta\ll\epsilon_0$) in dispersion relation (1) have essentially no effect, although they do cause large changes in the value of the negative effective mass. We did not expect these variations to have an effect: Although this parameter does determine the instability growth rate, it does not appear in other expressions. Variations in ϵ_0, m, and M, in contrast, which cause substantial changes in the entire relation $\epsilon(p)$, have significant effects on all the plots versus U and l.

Let us summarize the results. The region of saturation (or quasisaturation) of the current on the static current–voltage characteristics of the ballistic current of the negative-effective-mass electrons has turned out to be unstable, as expected.[2–4] In other words, despite the absence of a static N-shaped negative differential conductance, the admittance is characterized by negative conductance over a broad range of the frequency

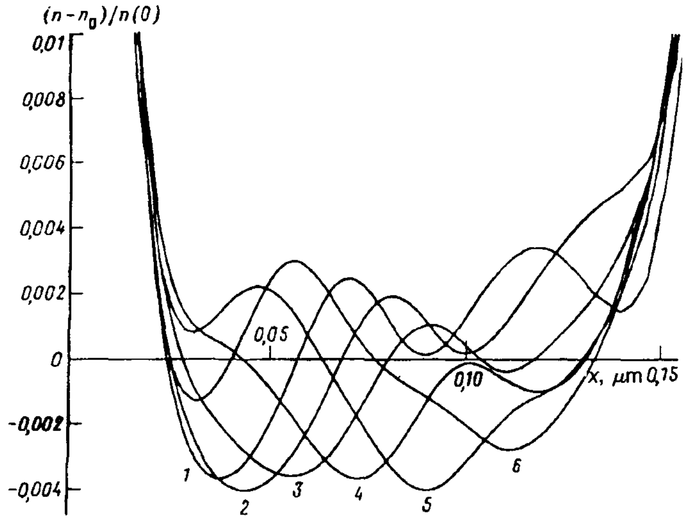

FIG. 3. Snapshots of the electron distribution $n(x,t)$ recorded during one period of the current oscillations (there is a time shift $\Delta t = 0.05$ ps between adjacent distributions) for a sample with $l = 0.175$ μm and the same parameters values as in Fig. 1. $U = 0.25$ V.

f here. The presence of a resonance frequency f_0 means that the susceptance changes sign with increasing f, being capacitive at $f < f_0$ and inductive at $f > f_0$. For parabolic and Kane dispersion relations, the susceptance is always capacitive. A change in the sign of the admittance with the frequency has been predicted previously for the case of quasiballistic transport involving the emission of one phonon during the traversal of the base,[6] with allowance for the periodicity of the dispersion relation in materials with a narrow band gap,[7] and also for the case in which the electron spectrum has heavy upper valleys in which ballistic electrons are scattered.[8] Generation of terahertz-range oscillations was recently predicted for the case of ballistic transport of electrons with a parabolic dispersion relation controlled by short gates.[9] The generation mechanism discussed in this letter is quite different from all other known mechanisms. An important distinctive feature of the present study is the calculation of the amplitude of the oscillations which are generated; such calculations would not be possible in the theory of a linear admittance.

If oscillations with a frequency even higher than here are to be generated, it will be necessary to reduce the critical base length l_c, i.e., the value of this length at which the oscillations arise (in the present case, it is $\simeq 0.125$ μm). A decrease in l_c would also help ensure that the electron transport is of a ballistic nature (see some reviews[8,10]). We would expect that the necessary decrease in l_c could be achieved by increasing the donor concentration n_0 and, correspondingly, the contact concentrations $n(0)$ and $n(l)$ by an order of magnitude.

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