TOTAL NEGATIVE PHOTOCONDUCTANCE IN SOLIDS AND POSSIBILITY OF A NEW TYPE OF INSTABILITY*

H. J. Stocker
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois
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Several mechanisms producing negative differential conductance (NC) in semiconductors and insulators have been investigated recently, in particular (a) field-dependent excitation to bands with lower effective masses (Gunn effect),[1] (b) field-dependent capture cross section of recombination centers,[2] (c) emission of acoustical phonons if the electron drift velocity exceeds the velocity of sound,[3] and (d) field quenching.[4]

In this paper we examine a new mechanism arising from interaction of photoexcited carriers with LO phonons which is capable not only of producing NC, but also a "total negative conductance" (TNC).[5,6] For TNC the average drift velocity $v(\mathcal{E})$ is, by definition, in a direction opposite to the electrical force $[v(\mathcal{E})<0]$, while for NC, we have $\partial v(\mathcal{E})/\partial\mathcal{E}<0$.

Briefly, the effect requires the following: (1) injection of electrons (or holes) by a monochromatic light source in the conduction band (valence band) at an energy E_1 just below the threshold energy for LO phonon emission,[7] where $E_1=E_g+z\hbar\omega_0$, $0.92<z<1.00$; (2) energy losses by acoustic phonon interaction during the lifetime of an electron sufficiently small so that the electron distribution remains nearly monoenergetic; (3) electron density sufficiently low so that e-e interaction is small compared with other scattering mechanisms. Upon the application of an electric field $\mathcal{E}$, the momentum losses, because of the threshold character of the LO phonon emission, are preferentially in the direction opposite to the drift velocity, as illustrated in Fig. 1. A detailed calculation, as summarized below, shows that the distribution can become such that the average velocity is negative.

The Boltzmann equation for the distribution function $f(k)\cong f_0(k)+f_1(k)\cos\theta$ (after expansion in spherical harmonics) leads to the following system of differentio-functional equations[8] (for a parabolic energy band):

$$\frac{-e\mathcal{E}}{3\hbar}\frac{1}{k^2}\frac{\partial}{\partial k}(k^2f_1)-\frac{f_0}{\tau_I(k)}-\frac{f_0}{\tau_0(k)}+\frac{(k^2+q_1^2)^{1/2}}{k}\frac{f_0((k^2+q_1^2)^{1/2})}{\tau_0((k^2+q_1^2)^{1/2})}+G(k)=0, \quad (1a)$$

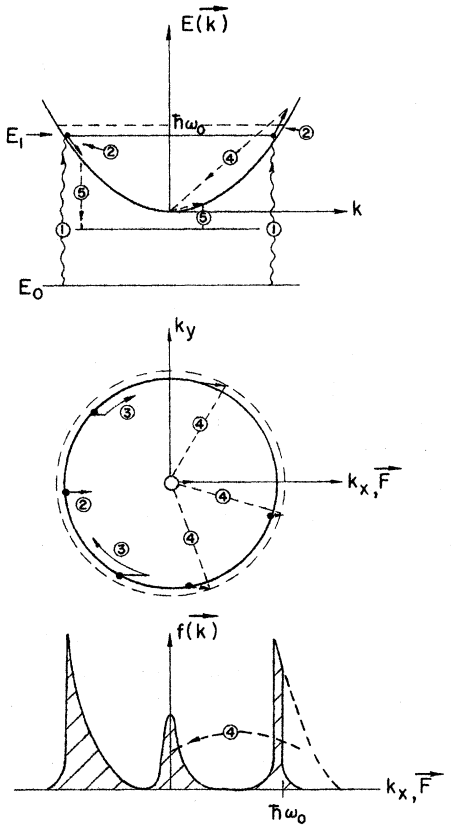

FIG. 1. Illustration of basic mechanism producing total negative conductance. Top: Conventional picture of the conduction band. Middle: Plane section in momentum space in a direction parallel to the electric force F. Bottom: Distribution function along the direction $(k_x, 0, 0)$. Electrons are transferred from a discrete impurity level E_0 to the conduction band by photon absorbtion (1) to an energy E_1 just below one LO phonon energy. The electrons gain energy from the electric field on the right-hand side (2), but lose energy on the left-hand side, since their initial velocity is in the opposite direction. Electrons with $E>\hbar\omega_0$ on the right-hand side quickly make a transition to the bottom of the band by emission of one LO phonon (4). The electrons are finally removed (5) from the conduction band by, e.g., a transition to excited impurity states. Elastic scattering due to impurities (3) is the dominant scattering mechanism for $E<\hbar\omega_0$. The preferential momentum losses, due to LO phonon emission (4), burn a hole into the distribution so that the average velocity is opposite to the direction of the electrical force.

$$\frac{-e}{\hbar}\mathcal{E}\frac{\partial f_0}{\partial k}-f_1\left[\frac{1}{\tau_l(k)}+\frac{1}{\tau_1(k)}+\frac{1}{\tau_0(k)}\right]=0. \quad (1b)$$

Solutions $f_0(k,z)$, $f_1(k,z)$ of the above system, valid for $\mathcal{E}<\hbar q_1\sqrt{3}/e\tau_0$, can be found[8] if (1) lifetime τ_l and impurity scattering time τ_1 are independent of energy,[9] (2) the optical-phonon emission probability is approximated by a step function $\tau_0^{-1}(k)=\tau_0^{-1}U(k-1)$, (3) the injection is assumed to be exactly monoenergetic at energy $E_1=\hbar^2z^2/2m^*$, $G(k)=NV\pi^{-2}k^{-2}\delta(k-z)$.

For arbitrary injection $G(z,z_0)$ the average velocity is then given by

$$v(\mathcal{E},z_0)=\frac{V}{3\pi^2}\frac{e\hbar}{m^x}\times\int_0^\infty dz\,G(z,z_0)\int_0^\infty dk\,k^3f_1(k,z). \quad (2)$$

We have integrated Eq. (2) numerically for a Gaussian distribution $G(z,z_0)=(2\pi\sigma)^{-1/2}\times\exp[-(z-z_0)^2/2\sigma^2]$, which is the approximate form of the injection from an impurity level to a conduction band. The dependence of $v(\mathcal{E},z_0)$ is shown in Fig. 2 for parameters appropriate to electrons in InSb and linewidth $\sigma=0.03\hbar\omega_0$. For injection energies between 0.92 and $1.00\hbar\omega_0$ NC occurs, and between 0.94 and $1.00\hbar\omega_0$ TNC exists.

In the calculation of the distribution function it was assumed a priori that the entire system was spatially homogeneous. In order to investigate the stability, we must now relax this assumption. In the following, we assume that the electron distribution adjusts quickly to a change in the local electric field $\mathcal{E}(x)$, so that the average electron velocity $v(\mathcal{E}(x))$ can be viewed as an instantaneous function of the local electric field. This approximation will be valid if the frequencies considered are such that $\omega\tau_\gamma\ll1$, where τ_γ is the relaxation time of the distribution (which is, at worst, of the order of τ_1). Under this condition, the macroscopic equations, neglecting diffusion and higher order corrections, are

$$j_d(x,t)=n(x,t)v[\mathcal{E}(x)], \quad (3)$$

$$\partial\mathcal{E}/\partial x=4\pi|e|/\epsilon(p-n), \quad (4)$$

$$\frac{\partial n}{\partial t}+\frac{\partial}{\partial x}j_d(x,t)=-\frac{n}{\tau_l}+G. \quad (5)$$

Here $j_d(x,t)$ is the drift current, and G is the generation rate, independent of x. The positive charge p (e.g., ionized donors) is assumed to be immobile and its time variation can be neglected if $\omega\tau_l\gg1$, the only case of interest. The system of Eqs. (3) to (5) formally always admits homogeneous and time-independent solutions, $n_0=p_0=G\tau_l$, $\mathcal{E}=\mathcal{E}_0$. The stability of these solutions can be investigated by linearization for small deviations δn, δp, $\delta\mathcal{E}$, and δv. Taking Fourier transforms

$$\delta n(x,t)=\frac{1}{(2\pi)^2}\times\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}d\omega\,dk\,e^{i(kx-\omega t)}\delta n(k,\omega) \quad (6)$$

and defining ξ by

$$\delta v=\left.\frac{\partial v(\mathcal{E})}{\partial\mathcal{E}}\right|_{\mathcal{E}_0}\delta\mathcal{E}=\xi\delta\mathcal{E}, \quad (7)$$

we obtain

$$\omega=kv(\mathcal{E}_0)+i[-(4\pi|e|/\epsilon)n_0\,\xi-1/\tau_l]. \quad (8)$$

A necessary condition for the growth of small

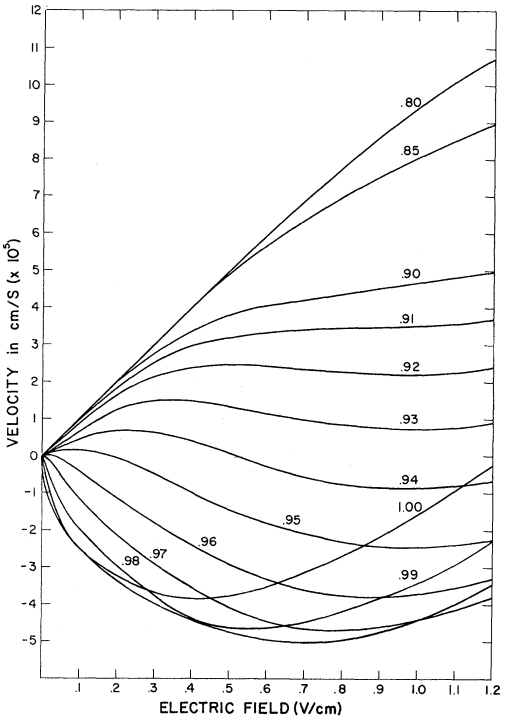

FIG. 2. Average velocity versus electric field as calculated from the Boltzmann equation [Eqs. (1) to (3)]. The numbers indicate the injection energy E_1 in units of one LO phonon energy $\hbar\omega_0$. For $0.94\hbar\omega_0<E_1\leq\hbar\omega_0$, the velocity is negative, i.e., total negative conductance exists. The linewidth for the Gaussian was assumed to be $\sigma=0.03\hbar\omega_0$. Parameters: $\tau_l=10^{-10}$ sec, $\tau_1=10^{-11}$ sec, $\tau_0=10^{-12}$ sec, $m^*=0.016m$, and $\hbar\omega_0=0.0244$ eV.

deviations is thus that the slope ξ be negative and of magnitude

$$|\xi| > \frac{\epsilon}{4\pi|e|}\frac{1}{n_0\tau_l} = \frac{5.52\times10^5\times\epsilon}{n_0\tau_l}. \quad (9)$$

If condition (9) is not fulfilled, we conclude that the system is stable and that TNC may be observed. To predict what happens if Eq. (9) is fulfilled requires a full nonlinear analysis, and depends to some extent on boundary conditions and the external circuit. In general, there will be a range in which a stable inhomogeneous solution exists and a range in which there will be oscillating solutions similar to the Gunn effect. In analogy to the Gunn effect it is to be expected that there will be a wide variety of modes of operation and that sample inhomogeneities will serve as nucleation centers.

The experimental conditions for the observation of TNC and the associated instability appear achievable. The requirement that the distribution remains nearly monoenergetic for $E_1 < \hbar\omega_0$ is one of the prerequisites for the observation of oscillatory photoconductivity in semiconductors, which recently has been found in many materials[10] for $T < 30°K$. The computer calculations indicate that both NC and TNC disappear for linewidths $\sigma \geq 0.06\hbar\omega_0$, i.e., larger than 1.5-2 meV. The linewidth of optical transitions between ground state and excited states of impurities in semiconductors has recently been observed to be of the order of 0.2 meV.[11] The broadening due to monoenergetic injections therefore does not appear to be a problem if a suitable impurity level is used and if a light source of the correct frequency and sufficient intensity is available. Specific examples of optical transitions which could be used are transitions from deep acceptor levels in InSb like Au^- (ionization energy 32 meV), Au^{--} (66 meV), and Ge (~110 meV) to the conduction band at $E_1 = 0.95\hbar\omega_0$. With $E_G = 235$ meV, $\hbar\omega_0 = 24.4$ meV. These would require photon energies of 225, 192, and 143 meV, respectively. A preliminary experiment should determine which of these transitions is best from the point of view of linewidth and competing optical-absorption processes. Photon-assisted intrinsic optical absorption will be negligible at 4°K but competing transitions from valence band to acceptor level may require careful control of doping. Since the lifetime of electrons in InSb is of the order 3×10^{-10} sec, $|\xi| \lesssim 10^6$ cm^2 V^{-1} sec^{-1}, a generation rate of 10^{20} photons sec^{-1} cm^{-3} is required. According to Eq. (9), for a sample of 1 mm^3, the minimal power should be ~5 mW. A laser source is clearly desirable. An additional problem is the reduction of the residual ohmic current $j_0 = \sigma_0\mathcal{E}$ so that $j_0 \ll |ej_d| = |en_0v(\mathcal{E})|$. j_0 may be due to the thermal carriers, impurity band conduction, or background radiation. By compensation, operation at liquid-helium temperature, and suitable experimental arrangements these contributions can largely be eliminated.

An attraction of the proposed scheme is that both the $v(\mathcal{E})$ characteristic (by changing the photon energy) and the density n_0 can be varied with little effort. The dependence of the instability on these parameters can therefore be studied easily.

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