Nonequilibrium Electron-Hole Plasma in GaAs Quantum Wells

Ralph A. Höpfel and Jagdeep Shah
AT&T Bell Laboratories, Holmdel, New Jersey 07733

and

Arthur C. Gossard
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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We demonstrate the existence of nonequilibrium between electrons and holes in the semiconductor GaAs under the influence of high electric fields. Hot-electron distributions in the presence of a cool majority hole plasma are observed. The measurement of the electron-energy-loss rate under these conditions allows the first experimental determination of the energy transfer by electron-hole Coulomb scattering in a semiconductor.

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Energy transfer from the carrier plasma to the lattice in semiconductors has been studied in both time-resolved[1] and steady-state[2] experiments. The research on energy transfer *within* the plasma by carrier-carrier scattering is in a very early stage and only a few experiments have been reported so far.[3–5] These experiments have been made in experimental ranges where either rapid, total thermalization by carrier-carrier scattering could be assumed,[1,2] or the initial relaxation process was studied, where electron-electron scattering and polar optical phonon emission are dominant.[3–5] For this reason, one important energy-transfer mechanism in an electron-hole plasma, the energy transfer between electrons and holes by electron-hole Coulomb scattering, has not been studied at all experimentally. This process is of fundamental interest and also of importance in device physics since it governs carrier transport in many bipolar devices, where a two-component plasma and high electric fields are present.

In this Letter we report the first experiment investigating electron-hole energy transfer in a semiconductor. The experiments are performed by injection of *minority* electrons in *p*-doped GaAs layers by use of picosecond photoexcitation. By measuring simultaneously (1) the electron velocity by a time-of-flight technique, (2) the luminescence spectra, and (3) the hole current as a function of the applied electric field, we are able to determine quantitatively the energy distribution of the electrons, the hole temperature, and the total energy-loss rate of minority electrons in a hole plasma. The most striking result of our studies is the observation of a *nonequilibrium plasma state with different distribution functions for electrons and holes.* The distribution functions of minority electrons at high fields are found to be "hot" distributions in contrast to the hole plasma, which remains close to room temperature. The total energy-loss rate per electron is found to be much larger in the presence of a hole plasma than in the absence of holes. The difference of the two rates is due to energy loss by electron-hole scattering, which provides *net energy transfer* from electrons to holes in the nonequilibrium state.

In our experiment, a pulsed, high electric field is applied along the planes of layers of 90-Å *p*-modulation-doped[6] GaAs quantum wells. Minority electrons and additional holes are injected by 6-psec laser pulses ($\lambda = 606$ nm). The minority electrons drift in the high electric field to the positive contact with a drift velocity v_d. Their space charge is screened by the majority holes. From the duration of the photocurrent pulse[7,8] ("time of flight") the drift velocity and thus the electron mobility (μ_e) in the high electric field (**E**) are directly obtained ($v_d = \mu_e|\mathbf{E}|$). Since we know that the input power per electron, $e\mu_e|\mathbf{E}|^2$, in steady state must equal the energy-loss rate,[2] this part of the experiments also determines the total energy-loss rate of the minority electrons. Time-integrated luminescence spectra and the hole current are simultaneously measured.

All measurements are done at room temperature, in quantum well structures grown by molecular beam epitaxy: The layer thicknesses are $d_1 = 90$ Å (GaAs), $d_2 = 54$ Å (AlGaAs *p* doped with Be to 2×10^{18} cm^3), and $d_3 = 323$ Å (undoped AlGaAs between the two layers). This structure was grown in twenty periods on a semi-insulating GaAs substrate. The room-temperature properties are $p = 4.2\times10^{11}$ cm^{-1} (hole concentration per GaAs layer), $\mu_p = 220$ cm^2/Vs (hole mobility), lifetime of photoexcited carriers is ~ 1 ns. Ohmic *p*-type contacts with open distances of 50 μm were made by alloying of AuZn (1000 Å, 5% Zn) at 480 °C, followed by a mesa etch to define a rectangular structure (50×100 μm^2) of homogeneous electric field. The electric field is applied in 10-ns pulses at 4-MHz repetition rate, synchronously with the laser pulses. The laser pulses are focused on an area of 2 μm (in field direction) $\times$ 20 μm (perpendicular to the field direction). Typical photoexcited-carrier densities are 5×10^9 cm^{-2} per layer.

The drift velocities of the injected minority electrons are plotted in Fig. 1 as a function of the applied field: The drift velocity of the electrons increases nearly linearly with a low-field mobility of about 1500 $cm^2/V\cdot s$. This low value, as compared to the intrinsic mobility of ~8000 $cm^2/V\cdot s$ in GaAs at 300 K, indicates that the presence of the high-density hole plasma causes strong momentum relaxation by electron-hole Coulomb scattering. After a peak velocity of 1.1×10^7 cm/s the velocity decreases at fields higher than 8 kV/cm. This negative differential mobility is due to real-space transfer of hot electrons into the low-mobility X minimum of AlGaAs, as has been shown in Ref. 8. The drift velocity of the majority holes is also plotted in Fig. 1 as a function of the electric field. The mobility is constant up to fields of 12 kV/cm, but drops by a few percent at higher fields. The qualitative conclusion from these data is that the (minority) electrons are strongly heated in the electric field, showing even negative differential mobility by transfer of hot carriers. In contrast, the holes seem to stay cool, since the hole transport is linear up to fields of 12 kV/cm.

Quantitative evidence is obtained from the photoluminescence data as well as the analysis of the hole-transport data. The photoluminescence spectra (inset, Fig. 2) have an exponential high-energy tail extending over more than 125 meV. (The shoulder at 1.54 eV is due to transitions from the second conduction subband.) This shows that the distributions of electrons and holes in this energy range can be characterized by "temperatures."[9,10] This does not imply that the electron distribution function is fully thermalized to one temperature in the whole energy range, as is the case for the high-density hole plasma, where hole-hole scattering establishes a thermal distribution.[2] However, since the dominant part of the electrons is within this energy range, the model of a thermalized distribution function can be used to quantify our experimental findings on the electron energy distribution. Curve *a* in Fig. 2 shows the electron temperatures obtained in this manner as a function of the applied electric field. The electron temperature reaches 650 K at fields larger than 8 kV/cm. The electron temperatures in this range are much *higher* than the hole temperatures which are determined in *two independent* ways: (1) From the slight change of the drift mobility measured at high electric fields (Fig. 1), the heating of the holes is obtained. The room-temperature mobility of holes is limited mainly by nonpolar optical phonon scattering[11] with a dependence of the mobility on temperature as $\mu_p \propto T^{-2.3}$. The same dependence has been experimentally observed for GaAs-AlGaAs quantum wells.[12] By a numerical evaluation of the theory of nonpolar optical-phonon scattering[13] that successfully describes this $\mu_p(T)$ dependence, we separate the contributions of lattice temperature and carrier temperature and obtain a dependence of the mobility on the hole temperature as $\mu_p \propto T_h^{-0.9}$ at 300-K lattice temperature. From this we deduce the hole temperature

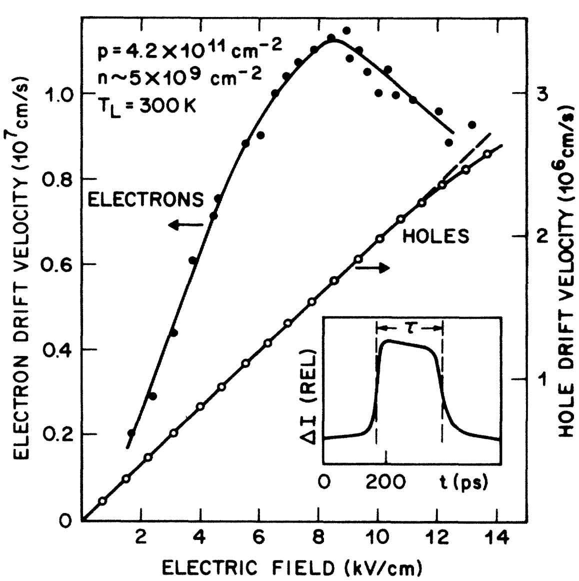

FIG. 1. Drift velocities obtained from time-of-flight experiments (electrons) and from conductivity data (holes) as functions of the electric field. Inset: The photocurrent signal ΔI as seen on a signal-averaged sampling oscilloscope for a field of 8 kV/cm and a drift length of 25 μm. From the drift time τ the electron drift velocity is directly obtained (Ref. 8).

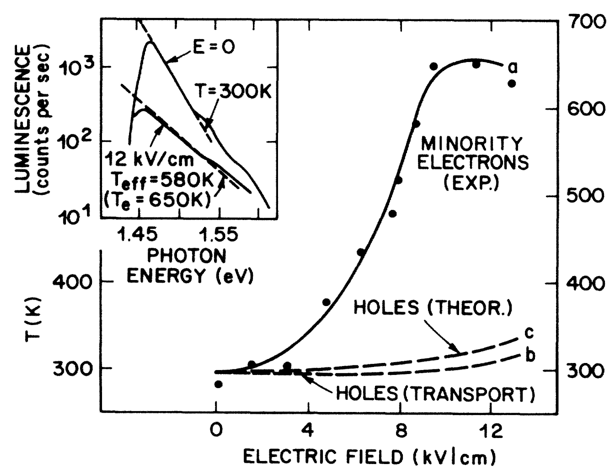

FIG. 2. Carrier temperatures of electrons (experimentally determined, curve *a*) and holes (from transport data, curve *b*, and energy loss theory, curve *c*) vs electric field. Inset: The luminescence spectra at $|\mathbf{E}|=0$ and $|\mathbf{E}|=12$ kV/cm.

as a function of electric field as shown in Fig. 2 (curve *b*). (2) A similar result is obtained by calculation of the hole temperature with use of the standard formalism for energy-loss rates[13] and the experimental values of the electron-phonon coupling constant[2] (curve *c*). Both *b* and *c* represent strong evidence that the holes are at a temperature below 350 K and therefore much *cooler* than the hot electrons.

In Fig. 3 the measured carrier temperatures are plotted as a function of the input power per electron, which is equal to the total energy-loss rate per electron. Plotting the carrier temperature as a function of the energy-loss rate allows a comparison of the experimentally determined total energy-loss rate of the minority electrons in the hole plasma with the known energy-loss rate $\langle \delta\epsilon/\delta t\rangle_{\text{e-ph}}$ of majority electrons,[2,13] when no holes are present and only energy loss to the lattice by polar optical phonon emission is possible. Figure 3 shows that the temperatures of minority electrons in a hole plasma, for a given energy-loss rate per carrier, are much lower than those expected for the majority electrons. In other words, *the energy-loss rate of hot minority electrons in a cool hole plasma is higher (by about a factor of 2) than the energy-loss rate of majority electrons in the absence of holes.*

We interpret these results in the following way: Electrons gain much more power per carrier in the electric field than the holes, since $\mu_e >> \mu_h$. In addition, holes are coupled more strongly to the lattice and therefore have a higher energy-loss rate to the lattice.[2] This drives the electron-hole plasma out of thermal equilibrium to a state where electrons and holes have drastically different distribution functions. Our experiments show that the two different distributions can be characterized by two *different* temperatures ($T_e >> T_h$). In this nonequilibrium state net energy transfer takes place by electron-hole Coulomb scattering.[14] This interaction tends to change the electron distribution function towards a *lower* temperature. The minority electron distribution function therefore is the result of *two* energy-loss mechanisms, electron-phonon interaction as well as electron-hole scattering.

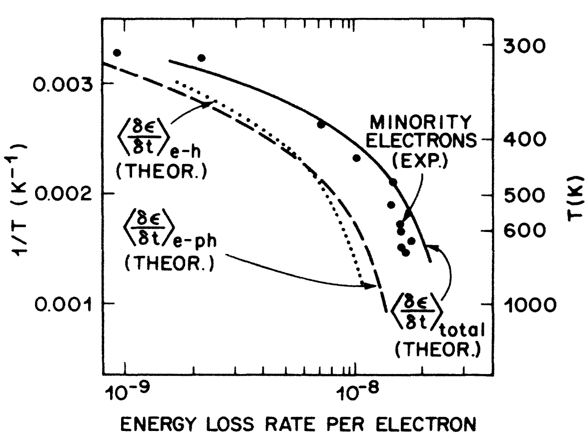

FIG. 3. Carrier temperatures as a function of the electron-energy-loss rate for the different scattering mechanisms (electron-phonon scattering, electron-hole scattering, total energy loss) and experimental results (circles).

In order to estimate theoretically the net energy-transfer rate from electrons to the holes in the nonequilibrium state, we use a solution of the Fokker-Planck equation, which has been derived for the analogous problem in a gas plasma, the energy transfer between electrons and ions by Coulomb collisions.[15,16] For both components described by Maxwell-Boltzmann distributions at T_e and T_+, respectively, the energy transfer is given by

$$\left\langle \frac{\delta\epsilon}{\delta t}\right\rangle_{\text{e-h}} = k_B \frac{\delta T}{\delta t} = \frac{8n_+ Y_{ei}}{3\sqrt{\pi}}\frac{m}{M}\frac{k_B(T_e - T_+)}{(2k_B T_+/M + 2k_B T_e/m)^{3/2}}$$

with $Y_{ei} = 4\pi(Ze^2/4\pi\kappa\kappa_0 m)^2 \ln\Lambda$, where

$$\Lambda = 3(4\pi\kappa\kappa_0 k_B T_e)^{3/2}/2Ze^3(\pi n)^{1/2}.$$

M and m are the two different masses, Z the ion charge (in our case equal to 1), and n, n_+ the two different carrier concentrations. k_B is the Boltzmann constant; $\kappa\kappa_0$ accounts for the dielectric properties of the background medium. Using the values of our experiment (translated into three-dimensional values of plasma densities), we obtain an energy-transfer rate $\langle\delta\epsilon/\delta t\rangle_{\text{e-h}}$ as shown in Fig. 3. Taking the sum of $\langle\delta\epsilon/\delta t\rangle_{\text{e-h}}$ and $\langle\delta\epsilon/\delta t\rangle_{\text{e-ph}}$ gives the total energy-loss rate $\langle\delta\epsilon/\delta t\rangle_{\text{total}}$, which is very close to our experimental data. The quantitative agreement must not be overinterpreted, since this theory of electron-hole scattering is exactly valid only for a three-dimensional plasma. An exact, two-dimensional calculation of the energy transfer by electron-hole collisions, including two-dimensional dynamic screening, therefore would be of great interest. Furthermore, the question remains to be answered whether the minority electron distribution is thermalized in the entire range of the conduction band, or only in the observed range. Electron-electron scattering seems to be very effective even at electron concentrations as low as 5×10^9 cm^{-2}, causing an exponential energy distribution within at least 125 meV above the conduction band edge.[17] The various scattering mechanisms (polar optical-phonon emission, electron-hole collisions, and electron-electron scattering) still result in a thermal Maxwell-Boltzmann distribution in the observed range, although extremely short energy relaxation times are present (250 to 450 fs for electron-phonon and electron-hole scattering, 150 to 250 fs for the total energy relaxation).[18] Clearly, more theoretical work is needed to fully understand the distribution functions under these extreme conditions.

In conclusion, we have observed heating of minority electrons in the presence of a cool, high-density hole plasma in GaAs quantum wells. The nonequilibrium electron-hole plasma shows an exponential energy distribution of electrons up to at least 125 meV above the band edge, characterized by electron temperatures (> 600 K) that are much higher than the hole temperatures (< 350 K). This nonequilibrium situation is induced by high electric fields in combination with room lattice temperature, where the energy-loss rates of electrons to the lattice and to the majority holes become comparable. This allows the first experimental determination of the energy transfer by electron-hole Coulomb collisions in a semiconductor.

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[18]These values of the relaxation times τ are obtained from the energy-loss rates (Fig. 3), with use of $\langle d\epsilon/dt \rangle = k_B \Delta T/\tau$.