Negative Absolute Mobility of Minority Electrons in GaAs Quantum Wells

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We report the observation of *negative absolute* mobility of electrons (i.e., a drift toward the negative electrode) in *p*-modulation-doped GaAs quantum wells. This unusual effect results from "carrier drag" on the electrons by the high-mobility hole plasma via electron-hole scattering.

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Carrier-carrier scattering in semiconductors has recently been studied in a series of exciting experiments[1-4] that probe the ultrafast relaxation processes of injected carriers. These studies were mainly focused on the energy relaxation mechanisms of photoexcited electrons, caused by electron-phonon and electron-electron scattering. An important aspect of carrier-carrier scattering is Coulomb interaction between electrons and holes which causes both energy and momentum relaxation in a two-component semiconductor plasma. Recent experiments[5-7] have begun to give quantitative information on the electron-hole scattering processes.

An interesting fundamental physical question concerning electron-hole scattering arises when minority electrons are injected into a hole plasma of high mobility, subjected to an electric field. For sufficiently strong electron-hole interactions, do the electrons drift with the holes to the negative pole of the electric field, i.e., does the absolute electron drift velocity (mobility) become negative? This problem has been theoretically studied in a classical paper by McLean and Paige[8] who showed that, in the analogous case of minority holes in *n*-InSb, negative mobility should be possible at low temperatures. However, no experimental observation of negative absolute mobility has been reported—in contrast to numerous systems with negative *differential* mobility, which, however, is a completely different phenomenon.

This Letter presents experimental results demonstrating that minority electrons in the semiconductor GaAs do exhibit negative absolute drift mobility at low temperatures and low electric fields, i.e., electrons drift from the positive towards the negative electrode, in *p*-modulation-doped GaAs quantum wells at lattice temperatures up to $T_L \sim 90$ K. The negative drift of electrons results from the momentum exchange between electrons and holes, i.e., the "carrier drag" on the electrons by the drifting, high-mobility hole plasma.

The minority electron is measured by a new all-optical technique: Electrons are excited in the semiconductor hole plasma by a focused laser pulse, and the magnified spatial image of the time-integrated luminescence is studied as a function of the applied electric field. As will be shown later, the local luminescence intensity is proportional to the local electron concentration. Therefore the luminescence image directly reflects the spatial distribution of the injected minority carriers with and without electric field. The temporal evolution of the luminescence intensity is separately measured by picosecond time-resolved techniques. Combining both measurements allows the experimental determination of very low drift velocities v_d—depending on the carrier lifetimes τ_{rec} and the resolvable drift length l_d ($v_d \tau_{rec} \geq l_d$). Other techniques, such as measurements of the photocurrent,[6] are disturbed by trapping effects at low temperatures.[9]

p-modulation-doped multiple quantum-well structures,[10] in contrast to bulk semiconductors, can have both high carrier mobilities at low temperatures, and high carrier concentrations. This feature is essential for the experiment. Our structures have the following dimensions: $d_1 = 112$ Å (GaAs), $d_2 = 49$ Å ($Al_{0.48}Ga_{0.52}As$ *p* doped with Be), $d_3 = 294$ Å (undoped AlGaAs "spacer layer"[10] between GaAs and doped AlGaAs). This structure is repeated for twenty periods on semi-insulating GaAs substrate. The hole mobilities and concentrations per GaAs layer are $p_0 = 1.5 \times 10^{11}$ cm^{-2}, $\mu_p = 53\,800$ cm^2/V s (at 4.2 K), $p_0 = 1.8 \times 10^{11}$ cm^{-2}, $\mu_p = 3700$ cm^2/V s (at 77 K), determined by Hall measurements. Typical concentrations of injected minority carriers are $n \sim 3 \times 10^{10}$ cm^{-2} per layer, photoexcited by 6-ps laser pulses (wavelength 606 nm, repetition rate 4 MHz, focus diameter ~ 3 μm). The magnified photoluminescence

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image ($\times 13$) is scanned with a mechanical slit (width 50 μm), and spectrally analyzed to detect only the intrinsic band-to-band recombination ($\lambda \sim 820$ nm, $\Delta\lambda = 10$ nm). The spatial resolution is of the order of 2 μm, which allows optical measurements of drift velocities as low as 2×10^5 cm/s for carrier lifetimes of 1 ns (as in our samples).

Figure 1 shows typical luminescence images for different lattice temperatures T_L. At the lowest temperature $T_L = 15$ K, without applied electric field, the image is symmetric (curve *a*). With applied electric field (curve *b*), the image is shifted and distorted in the direction of the *minus* pole of the applied voltage. As temperature is increased, the drift becomes smaller (*c*), and vanishes at $T_L = 90$ K (*d*). Finally, at even higher temperatures (curve *e*, $T_L = 150$ K) the drift is in the direction of the positive pole, as expected for negatively charged particles. Curves *b* and *c* demonstrate that, at low temperatures and low electric fields, photoexcited electrons have *negative absolute mobility, i.e., electrons drift from the positively charged electrode towards the negatively charged electrode.*

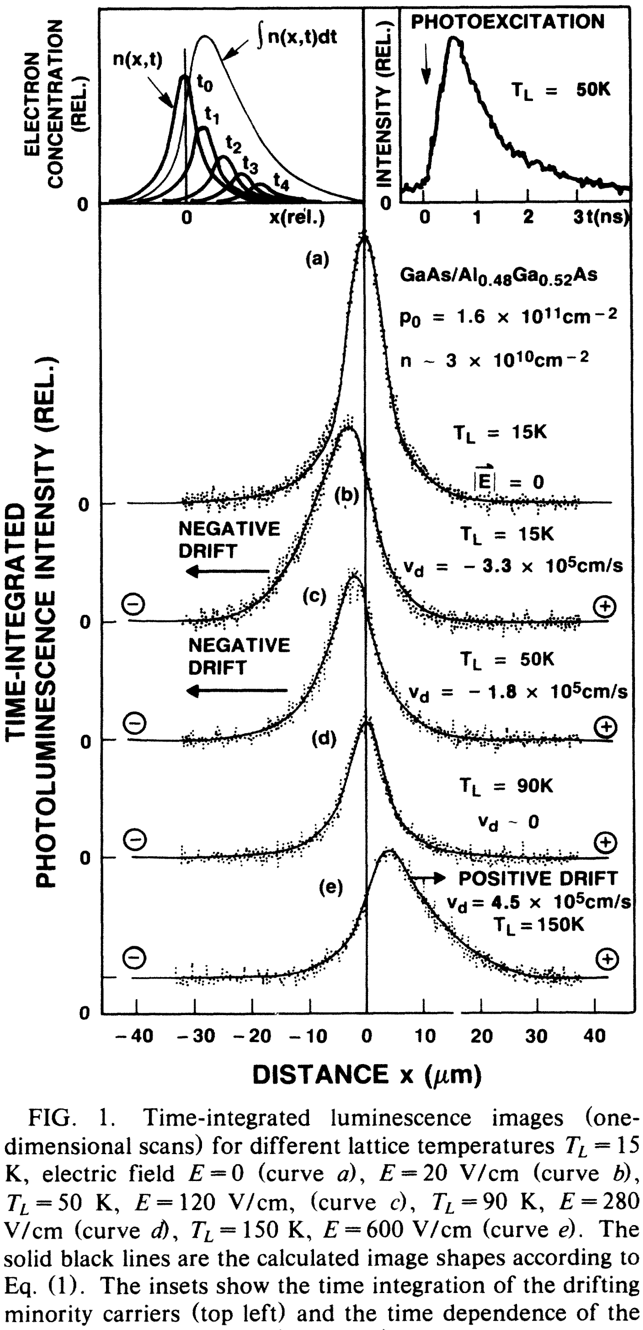

FIG. 1. Time-integrated luminescence images (one-dimensional scans) for different lattice temperatures $T_L = 15$ K, electric field $E = 0$ (curve *a*), $E = 20$ V/cm (curve *b*), $T_L = 50$ K, $E = 120$ V/cm, (curve *c*), $T_L = 90$ K, $E = 280$ V/cm (curve *d*), $T_L = 150$ K, $E = 600$ V/cm (curve *e*). The solid black lines are the calculated image shapes according to Eq. (1). The insets show the time integration of the drifting minority carriers (top left) and the time dependence of the luminescence intensity (top right) measured with a Si avalanche photodiode with a time resolution of 0.44 ns.

Quantitative analysis of these experiments is based on the linear relation between the local photoluminescence intensity from free-carrier band-to-band recombination and the local minority-carrier concentration.[11] For the case of a *p*-type semiconductor and weak injection of minority electrons ($n \ll p_0$), the time-integrated local luminescence intensity can be written as

$$\int I(x,t)\,dt = \int n(x - v_d t, t=0) f_l(t)\,dt, \qquad (1)$$

where v_d is the drift velocity of electrons. The function $f_l(t)$ is the time dependence of the minority electron concentration (proportional to the time dependence of the luminescence intensity for weak injection). The inset in Fig. 1 (top left) illustrates the time-integration process for a drifting and decaying (recombining) electron "packet." Diffusion is neglected since diffusion lengths are small compared to the size of the excitation spot. The time dependence of the luminescence intensity, $f_l(t)$, is measured with a Si avalanche photodiode (Fig. 1, top right), showing an exponential behavior with a decay time of ~ 1 ns. The experimental data are evaluated by our first determining the spatial profile of the photoexcited carriers in the absence of electric fields, $n(x, t=0)$. The luminescence image profiles with applied fields (curves *b*–*e* in Fig. 1) are then fitted by Eq. (1) with the drift velocity v_d as the only parameter. Equation (1) accurately describes the observed luminescence image: The solid curve and the experimental data, shown in Fig. 1, coincide within the experimental noise limit.

Data from several measurements at different temperatures and different electric fields E are shown in Fig. 2. The results can be summarized as follows: At low temperatures ($T_L = 15$ K) and low electric fields, the electron drift is negative. The highest measured value of the negative drift mobility is $-11\,500$ cm^2/V s. The negative mobility decreases both with electric field (at 15 K lattice temperature) and with increasing lattice temperature. At temperatures above 90 K the minority electron mobility becomes positive and increases with increasing temperature.

We interpret these observations in terms of strong momentum scattering of electrons by the high-density hole plasma ($p > 1.5\times10^{11}$ cm^{-2} in a 112-Å quantum well). One must resort to a numerical calculation of the coupled Boltzmann equations, as in Ref. 8, to obtain a solution in the general case. However, if the velocity distributions are drifted Maxwellians with drift velocities v_e and v_h, then it can be shown that these equations can be approximated by the hydrodynamic or fluid equations in the relaxation-time approximation,[12]

$$\frac{dv_e}{dt} = -\frac{v_e}{\langle\tau_{e\text{-}l}\rangle} - \frac{(v_e - v_h)}{\langle\tau_{e\text{-}h}\rangle} - \frac{eE}{m_e}, \qquad (2)$$

where $\langle\tau_{e\text{-}l}\rangle$ and $\langle\tau_{e\text{-}h}\rangle$ are the momentum relaxation times of electrons (averaged over the energy distribution function[11,12]) by lattice scattering and by Coulomb scattering in the *resting* hole plasma, respectively. The analogous equation for the holes is coupled with Eq. (2) via the term $(v_e - v_h)/\langle\tau_{e\text{-}h}\rangle$. Since the total momentum is conserved, it follows that, for weak minority-carrier injection ($n \ll p_0$), the electron drift mobility in steady state is given by

$$\mu_e = e(\langle\tau_{e\text{-}h}\rangle/m_e - \langle\tau_{h\text{-}l}\rangle/m_h) \times (1 + \langle\tau_{e\text{-}h}\rangle/\langle\tau_{e\text{-}l}\rangle)^{-1}. \qquad (3)$$

At low temperatures, $\langle\tau_{e\text{-}h}\rangle \ll \langle\tau_{e\text{-}l}\rangle$ (i.e., electron-hole scattering dominates), and so the electron mobility is simply the difference between the mobility of electrons relative to the holes and the mobility of holes relative to the lattice.

This allows an understanding of the observed negative absolute mobility at low temperatures: The electron mobility in a resting hole plasma can be approximated by ionized-impurity scattering,[7,8] because of the high ratio of the effective masses. Comparable impurity concentrations in GaAs[13] cause electron mobilities much lower (<2000 cm^2/V s) than the low-temperature hole mobilities ($>50\,000$ cm^2/V s at 4.2 K). Thus the absolute electron mobility according to Eq. (3) is expected to be negative at low temperatures. With increasing temperature, the hole mobility decreases rather rapidly[14] to $\mu_p \sim 200$ cm^2/V s at 300 K, whereas the electron mobility relative to holes is expected to increase as in the case of ionized-impurity scattering.[11] This model therefore predicts that the electron mobility will go through zero and become positive at higher temperatures, in agreement with the observations. The behavior of electron mobility with electric field can be understood in the same manner since the carrier temperatures increase with increasing electric field.[15]

Quantitative comparison of the measured negative electron mobility and our theoretical model is shown in Fig. 2: The temperature dependence of the minority electron mobility is plotted (dashed line) according

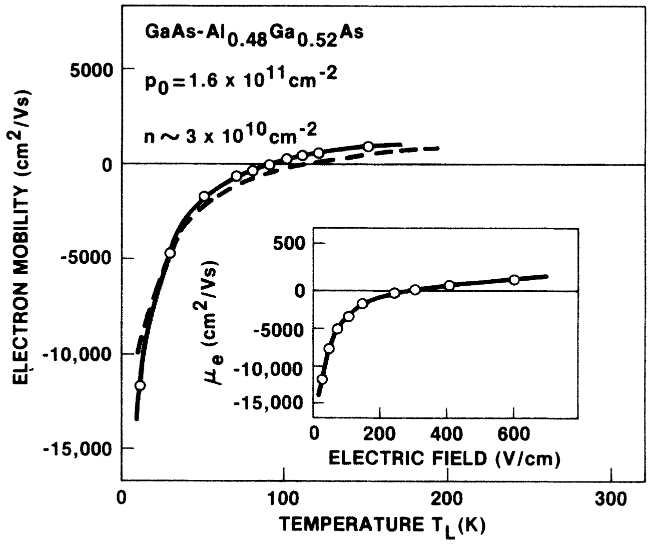

FIG. 2. Electron mobility as a function of the lattice temperature for low electric fields. Circles and solid line: experiment. Dashed line: theory according to Eq. (3). Inset: Mobility as a function of electric field at lattice temperature $T_L = 15$ K.

to Eq. (3), with use of the measured values of the hole mobility. The electron-hole momentum scattering times are estimated from ionized-impurity scattering in comparable (heavily doped) bulk GaAs.[13] It is obvious from Fig. 2 that Eq. (3) gives the right qualitative behavior; the theoretical curve is very close to the experimental values. Quantitative interpretation of this agreement, however, is problematic as a result of a strong effect of the photoexcitation on the hole mobility and concentration in heterostructures, which has been explained by trapping effects in AlGaAs.[9] Similar effects are present in the structures used in our experiments. They reveal high negative photoconductivity with a decay time of ~ 2.5 ms (at 15 K), as well as a small positive photoconductivity signal with a decay time of ~ 20 ns. Both effects clearly are not related to the minority-carrier dynamics in GaAs where the luminescence decays with a lifetime of 1 ns. Therefore, the local hole concentrations and mobilities may be different from the values obtained by the total-current measurements. Furthermore, these effects make it impossible to study the negative drift effect by photoconductivity alone (which should be seen as a negative photocurrent signal) and show the necessity and strength of the optical experiment.

Explicitly, for the theoretical curve in Fig. 2 we use values for $\langle\tau_{e\text{-}h}\rangle$ from ~ 40 fs (below 30 K) up to ~ 100 fs (>100 K). This corresponds to mobility values of ~ 1000 to ~ 300 cm^2/V s. Because of the discussed difficulties in determining the local hole mobility, these numbers should be regarded only as first estimates of $\langle\tau_{e\text{-}h}\rangle$. Regardless of the exact values, our experiments show that electron-hole scattering is an extremely effective momentum scattering process for injected minority electrons in high-density hole plasmas. Also in photoexcited electron-hole plasmas, electron-hole scattering should cause rapid momentum relaxation, which may explain the recently measured orientational relaxation times of less than 200 fs in photoexcited bulk GaAs at 77 K.[2]

In summary, we have observed negative absolute drift mobility of minority electrons in the high-mobility hole plasma of GaAs/AlGaAs quantum wells. Injected electrons drift from the positive to the negative electrode. The effect is explained by "carrier drag" via electron-hole scattering, which is shown to be the dominant electron-scattering process in this system.

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[1]W. H. Knox, C. A. Hirlimann, D. A. B. Miller, J. Shah, D. S. Chemla, and C. V. Shank, Phys. Rev. Lett. **56**, 1191 (1986).

[2]J. L. Oudar, D. Hulin, A. Migus, A. Antonetti, and F. Alexandre, Phys. Rev. Lett. **55**, 2074 (1985), J. L. Oudar, A. Migus, D. Hulin, G. Grillon, J. Etchepare, and A. Antonetti, Phys. Rev. Lett. **53**, 384 (1985).

[3]C. H. Yang and S. A. Lyon, Physica (Amsterdam) **134B+C**, 305 (1985).

[4]A. F. J. Levi, J. R. Hayes, P. M. Platzmann, and W. Wiegmann, Phys. Rev. Lett. **55**, 2071 (1985); M. Heiblum, M. I. Nathan, D. C. Thomas, and C. M. Knoedler, Phys. Rev. Lett. **55**, 2200 (1985).

[5]R. A. Höpfel, J. Shah, and A. C. Gossard, Phys. Rev. Lett. **56**, 765 (1986).

[6]R. A Höpfel, J. Shah, D. Block, and A. C. Gossard, Appl. Phys. Lett. **48**, 148 (1986).

[7]M. Morohashi, N. Sawaki, and I. Akasaki, Jpn. J. Appl. Phys. **24**, 732 (1985), and references therein.

[8]T. P. McLean and E. G. S. Paige, J. Phys. Chem. Solids **16**, 220 (1960).

[9]M. J. Chou, D. C. Tsui, and G. Weimann, Appl. Phys. Lett. **47**, 609 (1985).

[10]For a review on modulation-doped quantum-well structures, see A. C. Gossard and A. Pinczuk, in *Synthetic Modulated Structures*, edited by L. L. Chang and B. C. Giessen (Academic, New York, 1985), p. 215.

[11]K. Seeger, *Semiconductor Physics* (Springer-Verlag, Berlin, 1982), 2nd ed.

[12]E. P. Gross and E. A. Jackson, Phys. Fluids **2**, 432 (1959); J. Foch and G. W. Ford, in *Studies in Statistical Mechanics*, edited by J. de Boer and G. E. Uhlenbeck (North-Holland, Amsterdam, 1970), Vol. 5.

[13]M. A. Krivov, E. V. Malisova, E. N. Mel'chenko, V. S. Morozov, M. P. Nikiforova, S. S. Khludkov, Yu. A. Grigor'ev, O. L. Egorova, and V. B. Osvenskii, Izv. Vyssh. Uchebn. Zaved. Fiz. **26**, 94 (1983) [Sov. Phys. J. **26**, 1047 (1983)].

[14]H. L. Störmer, A. C. Gossard, W. Wiegmann, R. Blondel, and K. Baldwin, Appl. Phys. Lett. **44**, 139 (1984).

[15]J. Shah, A. Pinczuk, H. L. Störmer, A. C. Gossard, and W. Wiegmann, in *Proceedings of the Seventeenth International Conference on the Physics of Semiconductors*, edited by J. Chadi and W. Harrison (Springer-Verlag, New York 1985), p. 345.