Bloch Transport of Electrons and Holes in Superlattice Minibands: Direct Measurement by Subpicosecond Luminescence Spectroscopy

Benoit Deveaud,[a] Jagdeep Shah, and T. C. Damen
AT&T Bell Laboratories, Holmdel, New Jersey 07733

and

Bertrand Lambert and Andre Regreny
Centre National d'Etudes des Télécommunications, 22301 Lannion, France
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The perpendicular transport of photoexcited electrons and holes in graded-gap GaAs-AlGaAs superlattices is directly determined by subpicosecond luminescence spectroscopy. We show that the electron and hole transport is through extended, Bloch-type states for superlattice periods <40 Å, and determine the mobility for such transport. Increasing the superlattice period to 60 Å reduces the mobility by a factor of 20, as a result of an order-of-magnitude reduction in the hole miniband width. Our results provide the first evidence of diffusion enhanced by potential steps.

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When the wave functions of carriers in the neighboring wells of a multilayered semiconductor heterostructure overlap significantly, the energy levels broaden into minibands with extended, Bloch-type states. These minibands are expected to lead to the transport of carriers perpendicular to the layers (Bloch transport), and many interesting aspects of transport in such superlattices (SL's) have been discussed by Esaki and Tsu.[1] With steady improvement in the quality of semiconductor heterostructures, investigation of perpendicular transport in SL's is becoming an increasingly active area of research.

Electron motion in the perpendicular direction has been established by a variety of techniques such as cw photoluminescence,[2,3] picosecond luminescence,[4,5] and electrical measurements.[6-9] However, these experiments have not clearly demonstrated that the electron motion occurred through Bloch-type miniband states. More knowledge about miniband states was obtained in the second group of experiments in which the energy width of the miniband[10] or the electron effective mass for perpendicular motion[11] was determined. However, these experiments have not provided a direct measure of the electron mobility, an important quantity for perpendicular transport. Also, these experiments dealt only with electrons and no evidence was obtained for the motion of holes in minibands.[12]

We report experiments which provide direct and quantitative information about perpendicular motion of electrons and holes in GaAs-AlGaAs superlattices. We demonstrate that the transport of photoexcited carriers, determined primarily by the holes, occurs via Bloch conduction, with an ambipolar mobility of ~ 1800 cm^2/V·s for barrier thickness ≤ 20 Å. This mobility is comparable to the mobility in an equivalent alloy. Furthermore, we show that the transport depends dramatically on the barrier thickness and we establish that the mobility is reduced by at least a factor of 20 when the barrier width is increased to 30 Å. Both the value of the mobility and its large variation with the barrier width provide direct evidence for Bloch transport. Our experiments also give new insight into the diffusion of carriers driven by potential steps.

The perpendicular motion of carriers was directly determined by our measuring subpicosecond time-resolved luminescence spectra[13] of stepwise graded-gap superlattice samples (GGSL) with an enlarged well (see the inset of Fig. 1). Each 1000-Å step and the enlarged well (EW) luminesce at distinct energies as shown by the cw luminescence spectrum in the inset of Fig. 1. Thus, the measurement of luminescence *spectra* at different delays directly determines the *position* of photoexcited carriers as a function of time.

Four different samples, grown by molecular-beam epitaxy, were investigated. In the three superlattice (SL) samples the SL period $(a+b)$ is kept constant (the samples are labeled a/b SL, where a is the well width and b is the barrier width measured in angstroms), and the Al composition x in the barriers is changed in steps of 2% every 800 Å (1000 Å in 10/10 SL), from 35% at the surface to 17% ~ 1 μm away. One EW is introduced in the last step (typically 2000 Å) to collect the carriers. The fourth sample was a reference graded-gap GaAlAs alloy ($a=0$) with x changing by 1% every 1000 Å (from 17% to 18%). Growth conditions[14] and cw photoluminescence experiments on these samples have been described elsewhere.[15]

Subpicosecond luminescence experiments, with a time resolution of <400 fs,[13] were carried out with a dye laser synchronously pumped by the frequency-doubled output of a compressed, mode-locked neodymium-doped

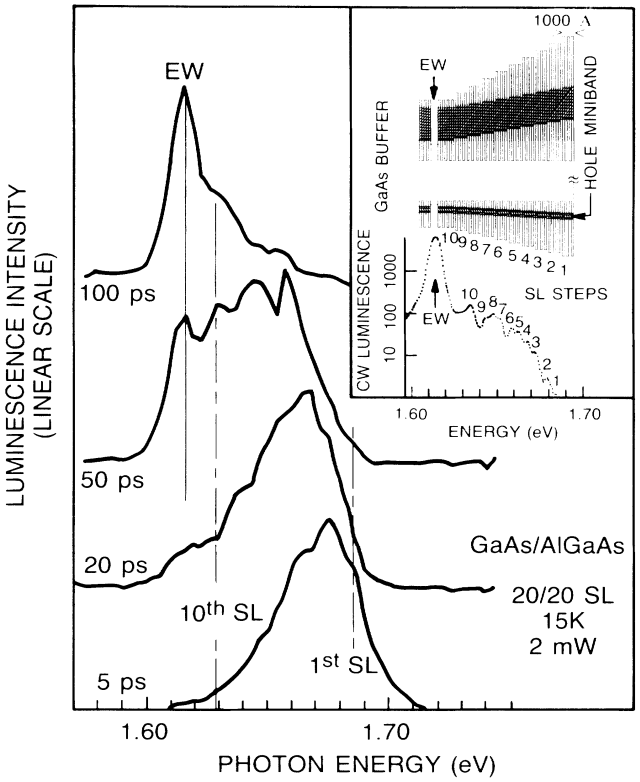

FIG. 1. The luminescence spectra of the 20/20 SL at various delays. The 5-ps spectrum shows that the carriers are created near the surface of the sample as the luminescence mainly originates in the first SL steps. For times as short as 100 ps, most of the carriers have been transferred into the EW. Inset: Schematic structure of the stepwise GGSL samples: ten steps of 1000 Å (or 800 Å) each with SL layers and the EW in the last SL. Also displayed is the cw luminescence spectrum (logarithmic scale) showing the ten SL luminescence peaks and the EW. The intensity of the EW luminescence already indicates a very efficient perpendicular transport.

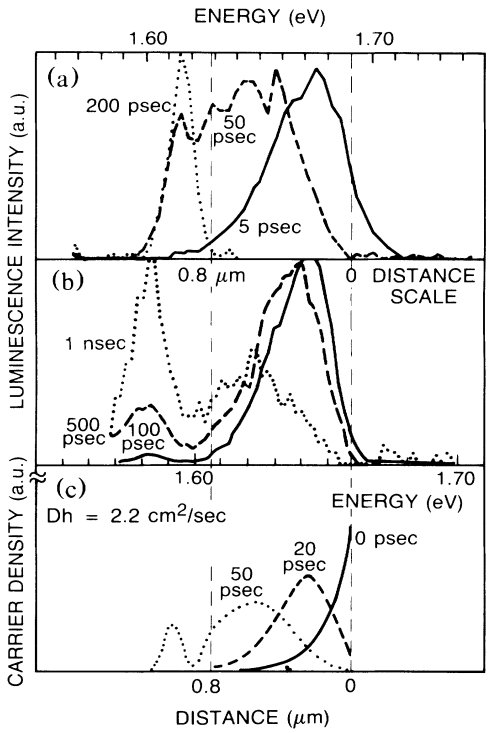

FIG. 2. Photoluminescence of (a) the 20/20 SL and (b) the 30/30 SL at different delays. The transport of carriers is dramatically slower in (b). (c) A model calculation using the step-driven diffusion model described in the text, with 800-Å steps and a diffusion coefficient of 2.2 $cm^2/V \cdot s$ (corresponding to an ambipolar mobility of 1800 $cm^2/V \cdot s$ at 15 K and to a hole mobility of 900 $cm^2/V \cdot s$).

yttrium-aluminum-garnet laser. The dye laser delivered <300-fs pulses at a repetition rate of 82 MHz and 6100 Å. Most of the spectra were taken with an average power of 2 mW, corresponding to 5×10^{12} photons/cm^2 per pulse, or to a density of $N_{eh} \simeq 1\times10^{17}$ pairs/cm^3. Unless specified, the experiments were performed at 15 K.

Typical spectra at four different delays after the excitation pulse are shown in Fig. 1 for the 20/20 SL. The luminescence peak energy clearly shifts as a function of delay, from $\simeq 1.68$ eV corresponding to the first SL steps near the surface to 1.615 eV corresponding to the EW. This shift exactly reflects the motion of the packet of photoexcited electrons and holes in the superlattice minibands. At 5 ps, the carrier packet is close to the surface, whereas at 50 ps it is centered in the last few SL steps, almost 1 μm away from the sample surface.

Figure 2 compares the results on the 20/20 and the 30/30 SL's. The difference is quite dramatic. After 100 ps, the carriers have not yet moved in the 30/30 sample, whereas in the 20/20 they are already in the EW.

In Fig. 3 we show the position of the center of the packet of carriers as a function of time in different samples.[16] The striking features are that (i) the movement is linear with time in all cases (i.e., an effective velocity can be defined for the motion of the carriers) and (ii) the velocities for 20/20 SL, 10/10 SL, and GaAlAs samples almost coincide, whereas it is *20 times smaller* in the 30/30 SL. *Since the transport in the 10/10 and 20/20 SL's proceeds at essentially the same speed as in the control alloy sample, we draw the important qualitative conclusion that the transport in these SL's proceeds via extended miniband states, i.e., it is Bloch transport.*

Since the potential does not vary continuously in our samples, and since the width of each step is larger than the mean free paths of carriers, the motion cannot be modeled by a quasielectric field.[17] We then consider that the transport proceeds by diffusion *in each SL step,* followed by a fall into the next step (of lower gap). Each step acts as a sink for the carriers coming from the

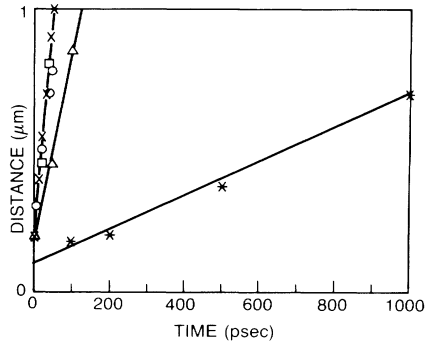

FIG. 3. The mean position of the carrier packet as a function of time in different samples: circles, 20/20, 15 K; crosses, 10/10, 70 K; triangles, 10/10, 15 K; squares, GaAlAs, 15 K; asterisks, 30/30, 15 K. Note the linear dependence in all cases, and the very large difference between the 20/20 and 30/30 samples. The three solid lines correspond to velocities of 5×10^4, 0.7×10^6, and 1.2×10^6 cm/s.

preceding one, as they are inhibited from going backwards to the larger gap step. The diffusion process then repeats in the next step. Thus the time travel N steps is N times the time to travel one step; this gives rise to linear motion of carrier packet with time.

We write the usual equations for diffusion,[18] except for the boundary conditions imposed by the steps. This brings three main differences compared to the usual diffusion process: The presence of a sink at the end of each step speeds up the diffusion (in each step),[19] the center of the carrier packet moves with time, and the motion of this packet is linear with time [see Fig. 2(c)]. Instead of having a packet broadening as $L=(Dt)^{1/2}$, we obtain a carrier packet moving by one step in a time $t\simeq0.2l^2/D$, where l is the step size. This linear motion with time is in very good agreement with the experimental observations in all four samples. By fitting the measured motion with this model, we have deduced the diffusion coefficient and hence the mobility for each sample. For the 20/20 SL, the diffusion coefficient is 2.2 cm^2/s and mobility is 1800 $cm^2/V\cdot s$. Note that, for a distance of 8000 Å, the step-driven diffusion model gives a transit time of 50 ps, whereas the standard diffusion model gives a broadening time ($=L^2/D$) of 3 ns for the same value of D.

Luminescence is observed only from those regions where both electrons and holes are present. In cw luminescence experiments with low excitation density,[15] the results were interpreted in terms of the transport of only electrons to the interior of the sample where they recombined with background holes due to residual doping ($p\sim10^{15}$ cm^{-3}). However, in our experiments $N_{eh}\sim10^{17}$ cm^{-3} is much larger than the residual doping. Since any separation of the two types of carriers would give rise to a large electric field between the two distributions at these densities,[20] the transport is expected to be ambipolar with mobility approximately twice the hole mobility.[18] The observation of luminescence from the interior of the sample thus implies a perpendicular motion of *both electrons and holes*.[21] Experimental evidence that holes are also moving comes from the fact that the luminescence intensity at long times is about the same as at short times and that there is no change in the transit time upon the increase or decrease of the excitation density by a factor of 10.

We thus deduce that the hole mobilities in the 20/20 SL and the control-alloy sample are the same and equal to 900 $cm^2/V\cdot s$. For such a mobility, the mean free path of the holes is larger than the superlattice period. Thus the transport is indeed *Bloch transport* in 20/20 SL. For the 30/30 SL, the mobility is deduced to be 50 $cm^2/V\cdot s$. In this case, the transport is not Bloch transport.

The drastic change in the transit times, and hence in the mobilities, observed in going from 20/20 to 30/30 SL is easily explained in terms of what is expected for the holes. From Bloch theory, the miniband width 2Δ is expected to vary as[22]

$$2\Delta\propto\exp\{-[(8m^*/\hbar^2)(\Delta E-E_i)]^{1/2}b\},$$

where b is the barrier width, ΔE is the band offset, and E_i is the miniband extremum position. At low temperature, the mobility of similar bulk samples is impurity limited, so that we can assume the scattering time in our SL's to be the same as in an equivalent alloy. The mobility of the carriers for perpendicular transport is then given by[22]

$$\mu=m^*_{\rm all}(\Delta d^2/\hbar^2)\mu_{\rm all},$$

where $\mu_{\rm all}$ is the mobility of the GaAlAs alloy, $m^*_{\rm all}$ the effective mass, and $d(=a+b)$ the period of the superlattice. In GaAs-AlGaAs SL's, the electron mobility is expected to reach the bulk value for a 70-Å period and is expected to be about the same for 30/30 and 20/20 SL's (different values would be found for other materials). The heavy-hole miniband width is expected to be 23 meV for the 20/20 SL and 2.5 meV for the 30/30 SL.[23] This is expected to lead to a reduction in Bloch mobility of holes by a factor of 4. Further reduction in the mobility of holes in the 30/30 SL can be expected for the following reasons. First, lifetime broadening associated with typical scattering times is comparable to 2.5 meV. This, as well as localization resulting from disorder effects,[24,25] will hinder Bloch transport. Second, the step in potential between two successive SL steps becomes of the order of or even larger than the miniband width so that unmatching effects can be expected.[22] Neither of these effects is important for electrons in 30/30 SL since the electron miniband width is large. Thus, the large observed difference in the transit time between 20/20 and 30/30 SL's results from the fact that the transport of photoexcited carriers is governed by hole mobility.

The mobility of the 10/10 samples is lower than that

of the 20/20 GGSL at 15 K ($\sim$500 cm^2/V·s). This is due to localization by layer-to-layer variation of the GaAs well thickness. These variations play a minor role in the other samples, but (taking a reasonable value for the thickness fluctuation of[25] 0.5 Å) give a localization energy as large as 10 meV in the 10/10 sample. The effective velocity increases with temperature in this sample (see Fig. 2), so that the transport is fully Bloch type at higher temperatures.

In conclusion, we have directly determined the perpendicular transport of photoexcited electrons and holes by measuring subpicosecond luminescence spectra at various delays following excitation. We have established that the transport is Bloch transport for 20/20 and 10/10 SL's and determined the mobility for such transport. A dramatic reduction in the mobility in the 30/30 SL (compared to that in the 20/20 SL) is observed and attributed to the reduction in the hole miniband widths.

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[a]Permanent address: Centre National d'Etudes des Télécommunications, LAB/ICM, 22301, Lannion, France.

[1]L. Esaki and R. Tsu, IBM J. Res. Dev. **4**, 61 (1970).

[2]A. Chomette, B. Deveaud, J. Y. Emery, A. Regreny, and B. Lambert, Solid State Commun. **54**, 75 (1985).

[3]K. Fujiwara, J. L. de Miguel, and K. Ploog, Jpn. J. Appl. Phys. **24**, L405 (1985).

[4]B. Deveaud, A. Chomette, B. Lambert, and A. Regreny, Solid State Commun. **57**, 885 (1986).

[5]A. Nakamura, K. Fujiwara, Y. Tokuda, N. Nakayama, and M. Hirai, Phys. Rev. B **34**, 9010 (1986).

[6]F. Capasso, K. Mohamed, A. Y. Cho, R. Hull, and A. L. Hutchinson, Phys. Rev. Lett. **55**, 1152 (1985).

[7]J. F. Palmier, C. Minot, J. L. Lievin, F. Alexandre, J. C. Harmand, J. Dangla, C. Dubon-Chevallier, and D. Ankri, Appl. Phys. Lett. **49**, 1260 (1986).

[8]D. V. Lang, A. M. Sergent, M. B. Panish, and H. Temkin, Appl. Phys. Lett. **49**, 812 (1986).

[9]R. A. Davies, M. J. Kelly, and T. M. Kerr, Phys. Rev. Lett. **55**, 1114 (1985).

[10]G. Belle, J. C. Maan, and G. Weimann, Solid State Commun. **56**, 65 (1985).

[11]T. Duffield, R. Bhat, M. Koza, F. de Rosa, D. M. Hwang, P. Grabbe, and S. J. Allen, Jr., Phys. Rev. Lett. **56**, 2724 (1986).

[12]Electrical measurements are interpreted as giving evidence for hole localization (Refs. 7–9).

[13]J. Shah, T. C. Damen, B. Deveaud, and D. Bloch, Appl. Phys. Lett. **50**, 1307 (1987).

[14]B. Deveaud, A. Regreny, J. Y. Emery, and A. Chomette, J. Appl. Phys. **59**, 1633 (1986).

[15]B. Lambert, B. Deveaud, A. Chomette, A. Regreny, and R. Romestain, in *High-Speed Electronics,* edited by D. H. Auston, Springer Series in Electronics and Photonics Vol. 22 (Springer-Verlag, Berlin, 1986).

[16]The spatial position of the carrier packet is obtained from the peak luminescence energy and from the cw luminescence energy for each SL step.

[17]F. Capasso, Annu. Rev. Mater. Sci. **16**, 263 (1986).

[18]S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).

[19]An increase in speed at a potential step was predicted by G. Baccarani, C. Jacoboni, and A. M. Mazzone, Solid-State Electron. **20**, 5 (1977).

[20]A separation between the electrons and the holes would lead to an electric field of as much as 8×10^7 V/cm [D. F. Nelson, Phys. Rev. B **25**, 5267 (1982)]. We have checked that an increase or a decrease by about an order of magnitude in the excitation density does not change the behavior of the carriers.

[21]This finding is consistent with previous measurements showing hole localization (Refs. 7 and 9) since the barrier widths and heights, and hence the hole miniband widths, are different in the two cases.

[22]F. Capasso, K. Mohammed, and A. Y. Cho, IEEE J. Quantum Electron. **22**, 1853 (1986).

[23]A. Chomette, private communication; the calculations were made for $x=0.3$ with $\Delta E_c=0.65\Delta E_g$.

[24]P. W. Anderson, Phys. Rev. **109**, 1492 (1958).

[25]A. Chomette, B. Deveaud, A. Regreny, and G. Bastard, Phys. Rev. Lett. **57**, 1464 (1986).