Observation of Carrier Localization in Intentionally Disordered GaAs/GaAlAs Superlattices

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The carrier localization and the inhibition of carrier transport along the growth axis (vertical transport) are studied by means of photoluminescence experiments performed at 1.7 K in purposely disordered GaAs/GaAlAs superlattices. When the well widths are randomly varied, minibands of extended states shrink and localized states are created in their tails. Consequently the vertical transport efficiency decreases and sharply vanishes when disorder induces fluctuations of the eigenenergies which are comparable to half of the unperturbed superlattice bandwidth. By an increase of temperature the vertical transport becomes thermally activated.

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The new ability to build heterostructures with control of the growth of each individual atomic layer has allowed access to fundamental physical effects, as well as novel electro-optical devices.[1] The best documented system is the GaAs/GaAlAs one: The growth of superlattices with virtually defect-free interfaces can be achieved by molecular-beam epitaxy. It is then inviting to construct random superlattices to test theories which deal with electron propagation in random lattices. The main idea is that of Anderson localization and of possible transitions (mobility edges) between extended and localized states.[2,3] The study of these properties in superlattices has already attracted some attention,[4–6] but to our knowledge no observation has ever been reported.

In this Letter, we report the first observation of carrier localization in intentionally disordered superlattices. By studying the low-temperature photoluminescence emitted by an enlarged well located far away from the region where carriers are photocreated, we are able to demonstrate that the vertical transport in the disordered superlattice is progressively inhibited when the disorder increases, and that it becomes thermally activated. These effects are associated with the disappearance of the superlattice extended states induced by disorder and by their replacement by spatially localized levels.

The investigated structures were grown in a molecular-beam-epitaxy (MBE) reactor on (100) laser-quality GaAs substrates and studied in photoluminescence and photoluminescence-excitation spectroscopy. Growth conditions and luminescence methods are described elsewhere.[7] The growth rate being constant in our system, the different well widths are obtained by our storing the correct growth times in the memory of the computer that controls the growth chamber. Each sample consists of (i) a GaAs buffer layer (1000 nm), (ii) a GaAs/GaAlAs superlattice SL2 (total thickness around 297 nm), (iii) a GaAs well W1 (5.83 or 7.25 nm), and (iv) a superlattice SL1. All layers are undoped.

The superlattices SL1 and SL2 are indentical and symmetrical with regard to W1. They are composed of 50 $Ga_{0.7}Al_{0.3}As$ barriers (constant thickness of L_b of 3 nm in all samples) and 40 GaAs wells. In the first sample, which is the reference sample, SL1 is a periodic superlattice and all of its 49 wells have the same width, $L_z = 3$ nm. In all the other samples, disorder has now been purposely introduced in the superlattices in the form of a random variation of the well widths L_z^i ($i = 1, \ldots, 49$). Note that L_z^i is averaged over the ith-well interface fluctuations and, hence, is not a whole multiple of one monolayer[7] and can be varied by a fraction of a monolayer. In each sample, L_z^i are random variables which follow a Gaussian distribution with mean value $L_z = 3$ nm and standard deviation S. Accordingly S characterizes the disorder introduced in each sample. We have grown six samples, with $S = 0.05$ nm, 0.1 nm, 0.283 nm (= 1 monolayer), 0.4 nm, 0.566 nm (=2 monolayers), and 0.849 nm (=3 monolayers). The reference sample corresponds to $S = 0$.

The width of the GaAs well W1 has been chosen larger than L_z by ten monolayers (fifteen in the sample with $S = 3$ monolayers) to obtain an energy level substantially lower than those generated by the periodic or disordered superlattices. This well W1 serves as a probe in luminescence studies to characterize the efficiency of the vertical transport of carriers in our structures.[8]

Photoluminescence experiments were performed by use of an argon laser (≈ 4579 Å) with a power density

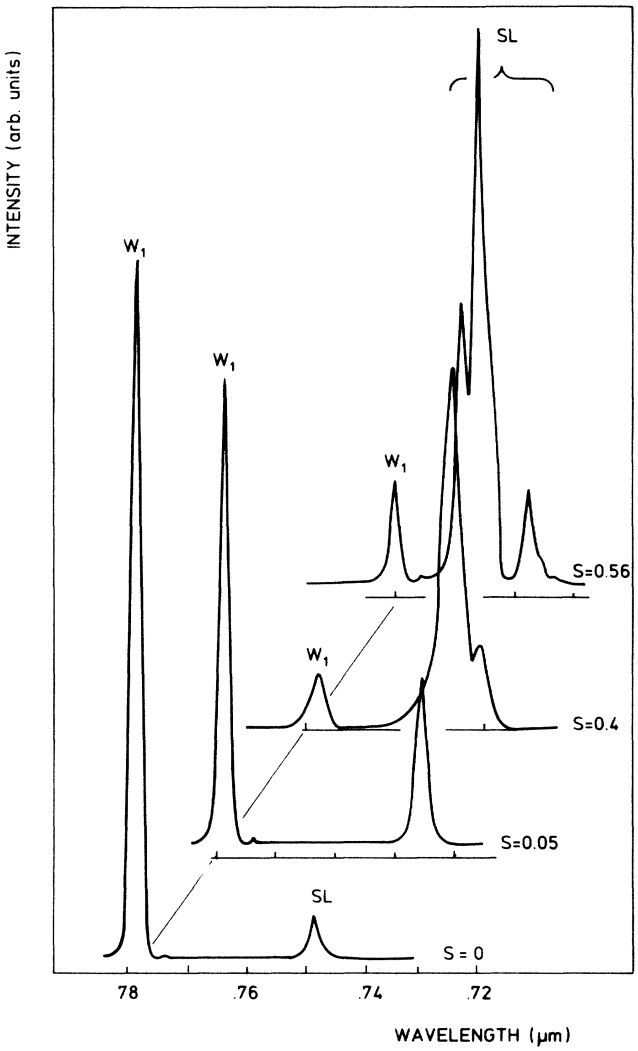

FIG. 1. Luminescence spectra of four SL's with increasing disorder at 1.7 K (laser wavelength 4600 Å). W1 and SL denote the luminescences arising from the enlarged well and the superlattice, respectively.

of 300 mW/cm^2. Thus, photocarriers were created in the first 100 nm of SL1. We show in Fig. 1 the luminescence spectra of several samples, including the reference sample, at 1.7 K. All the peaks are of excitonic origin. The lowest-energy peak arises from W1,[8] whereas all the others arise from SL1. As disorder increases, the SL1 photoluminescence spectrum consists of an increasing number of peaks. The very strong intensity of the W1 photoluminescence in the reference sample unambiguously demonstrates that a large part of the carriers photocreated in SL1 move along the z axis and become trapped in W1 where they recombine. Figure 1 clearly indicates that the efficiency of this vertical transport decreases with increasing disorder. It vanishes when $S > S_c$, where $S_c \approx 2.5$ monolayers: In the sample with $S = 3$ monolayers, the W1 peak is too small to be unambiguously attributed to a carrier transport from SL1; it could equally be due to the optical excitation of W1 by the luminescence of SL1.

In order to interpret the luminescence spectra, we have calculated the energy levels of the heterostructures.[9] In the absence of disorder, the energy levels are organized in minibands of extended states (wave functions delocalized over the whole structure). A localized level corresponding to W1 occurs below each miniband. Its wave function is essentially localized within W1. The W1 localized level is ≈ 55 meV (75 meV in the case of $S = 3$ monolayers) below the bottom of the first conduction miniband whose width is ≈ 70 meV. In the presence of disorder, the energy range corresponding to extended states shrinks and localized levels appear in its tails. They correspond to the largest and smallest wells in the SL1 and have wave functions localized over a finite portion of SL1. The W1 level is unaffected by the disorder. Ultimately, when disorder is large enough, the extended states disappear and all levels are localized. These energy-level features explain the data shown in Fig. 1: at low temperature the carriers photocreated in SL1 either move along the z axis and fall into W1 or are trapped in the disorder-induced tail states. Thus, an increase of the disorder diminishes the W1 photoluminescence to the benefit of the SL1 one, which itself exhibits structures due to the increasing number of different L_z^l.

As the observation of luminescence in the enlarged well requires both electron and holes, both electrons and heavy holes move along the growth direction (indeed the miniband width for holes is 8 meV, and disorder-induced states are less localized for holes than they are for electrons). As a matter of fact, calculations show that the trapping times for electrons and heavy-holes are comparable.[8] The efficiency of vertical transport may be characterized by the ratio $R = I_{W1}/I_{SL}$ where I_{SL} and I_{W1} are the integrated intensities of the SL and of the W1 luminescences, respectively. In fact, simple rate equations predict that $R = t_{W1}/t_{cap}$ where t_{W1} is the lifetime of the W1 level (essentially S independent) and t_{cap} the capture time from the superlattice into W1. The temperature (T) dependence of R shown in Fig. 2 confirms our interpretation of the drop of the W1 luminescence intensity in terms of carrier localization in disordered superlattices. In all cases R increases with T up to $T \approx 80$ K and then shows a slight decrease. As T increases, more and more carriers detrap from the tail states and become thermally activated in the extended states. They can therefore be again collected by W1, which leads to an increase of R. Note that W1 is deep enough in energy to preclude any significant detrapping. Two domains are apparent on the $R(T)$ curves

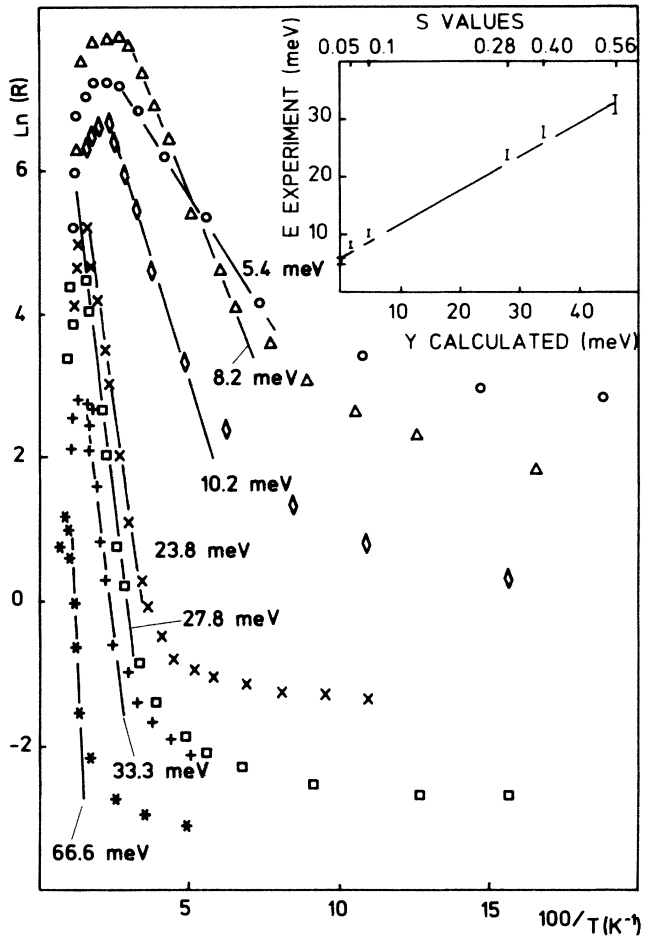

FIG. 2. Intensity ratio $R = I_{W1}/I_{SL}$ as a function of temperature for different values of disorder S (circles, $S=0$; triangles, $S=0.05$ nm; lozenges, $S=0.1$ nm; crosses, $S=0.283$ nm; squares, $S=0.4$ nm; plusses, $S=0.566$ nm; asterisks, $S=0.849$ nm). Inset: Experimental activation energy E vs the calculated energy distance Y between the deepest localized SL1 state and the lowest-lying extended SL1 state when it exists.

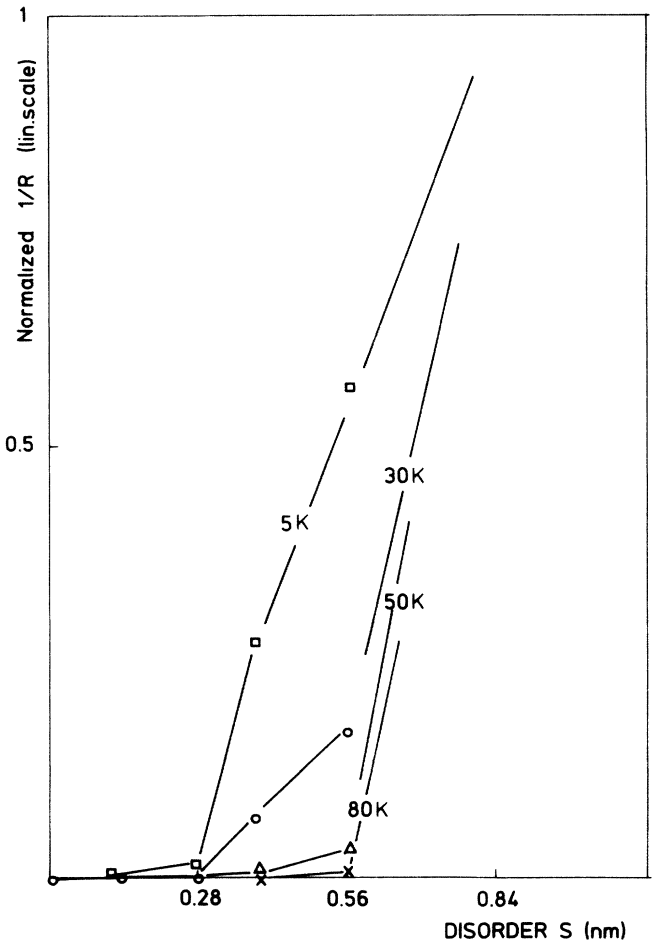

FIG. 3. Normalized intensity ratio $1/R$ as a function of disorder S for different temperatures. At each temperature, R has been taken equal to 1 for the most disordered sample ($S=0.849$ nm). Solid lines are only a guide for the eye.

of samples with $S < 0.849$ nm, (i) a weak increase of R which corresponds to the detrapping from levels close to the extended states ($L_z^l \approx 3$ nm) and which is followed by (ii) a steeper increase of R which arises from the detrapping from deeper levels. An activation energy E can be associated with this second process (see Fig. 2). The observed E are in good agreement with the calculated energy differences between the lowest-lying extended states and the deepest localized level (generated by the largest well actually introduced in SL1). Note that the activation is governed by the electrons since the hole tail states are more weakly bound than the electron ones. A further check of this interpretation is provided by photoluminescence excitation measurements which will be detailed in a future publication.

The saturation of R around 77 K is likely to be associated with the onset of optical-phonon scattering and will not be detailed here. For the most disordered sample ($S=3$ monolayers), previous considerations do not apply: All levels are localized and the transfer of carriers, activated above 77 K, is probably due to a hopping conduction assisted by phonons.[10]

In Fig. 3, we have plotted $1/R$ vs S at various temperatures. The most striing feature is the fairly abrupt transition of $1/R$ when S becomes larger than 2 monolayers. We believe this behavior to be characteristic of the Anderson transition, which is expected to take place when the "strength" of the disorder exceeds some definite value which leads to the localization of all eigenfunctions.[11] The behavior at 5 and 30 K is less clear, but is obscured by residual disorder. There are some difficulties in ascertaining the precise location of

this transition in our structures. They are not truly one-dimensional disordered superlattices but also exhibit some disorder in the layer plane which is due to the interface fluctuations.[7] The in-plane disorder, which is known to be correlated with the growth conditions,[12-14] can, however, be assumed to be constant in samples grown under the same conditions. Thus the analysis may, to a first approximation, be performed by consideration of only the disorder along the growth axis. Our work is the first observation of carrier localization in intentionally disordered superlattices. Localization due to unintentional disorder was recently observed by Capasso *et al.*,[12] when the total broadening mechanisms exceed the miniband width.

In a tight-binding analysis of the carrier-envelope function, our heterostructures can be identified with a series of single quantum wells (thickness L_z^l, bound states E^l) which are coupled by a nearly constant interaction energy (the barrier thickness is constant). The standard deviation D in E^l represents the strength of the disorder, which is site diagonal. When $D \approx B/2$ where B is the unperturbed conduction-band width, all the states should become localized. Now for a (3 nm)/(3 nm) superlattice, $B=70$ meV and $E^1=160$ meV. To obtain $D=B/2$, one should have wells with $L=3.9$ nm in the disordered superlattice.[15] Thus our tight-binding model predicts $S_c \approx 3$ monolayers. This value is in reasonably good agreement with the experimental S_c value deduced from the analysis of the transfer efficiency (see Fig. 3).

In conclusion, we have shown that the vertical carrier transport in intentionally disordered superlattices is drastically diminished when the disorder increases. In addition, it becomes thermally activated with an activation energy which increases with disorder. We have been able to correlate the efficiency of the vertical transport with the energy-level features of our heterostructures. We believe that intentionally disordered superlattices are ideal tools for the study of disorder effects, as the disorder can be controlled to a large extent.

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