Photoemission from a Superlattice and a Single Quantum Well

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(Received 2 May 1985)

We present the first experimental evidence of tunneling and transport of electrons from quantum states in a GaAs/GaAlAs superlattice or a quantum well to a GaAs surface activated to negative electron affinity. The photocurrent versus light excitation energy shows definite structures which appear exactly at the calculated energies of the allowed optical transitions between the quantized levels of the valence and conduction bands. The 300- and 30-K results for the superlattice are successfully compared to luminescence experiments, and could lead to the production of highly polarized electron beams.

PACS numbers: 73.40.Lq, 73.40.Gk, 79.60.Eq

Recent advances in crystal growth have stimulated numerous experimental[1,2] and theoretical[3] studies of two-dimensional structures, the so-called superlattices (SL) and quantum wells (QW). In such structures, obtained by alternating thin layers of different semiconductors, the variation in energy gaps produces potential wells with quantized levels. While many optical[4,5] or transport properties in the layer plane[6,7] are today well known, very few experiments on transport perpendicular to the layers[8–10] have been reported. However, the first measurements of electron-spin orientation in GaAs QW structures using optical circular polarization techniques suggested their potential use for highly polarized electron sources.[5]

We present here the first experimental evidence of tunneling and transport of electrons from quantum states in a GaAlAs/GaAs/GaAlAs QW or SL to the GaAs surface. We study the photoemission of samples containing a SL or a QW. Absorption of photons of energh $h\nu$ between the quantized levels of the structures promotes electrons from valence to conduction states. These electrons may appear in the GaAs conduction band by tunneling through the GaAlAs layers, and then reach the GaAs surface, activated to negative electron affinity (NEA)[11]: In this situation the vacuum level is lower than the bottom of the conduction band in the bulk solid, so that any conduction electron can escape into vacuum. It is then possible to detect free electrons which have been excited in the SL or QW and transported towards the surface.

A schematic sketch of the experiment in ultrahigh-vacuum conditions is shown in Fig. 1. The incoming light from a halogen lamp filtered by a monochromator is focused on a sample and the photoemitted current is collected on a positively biased grid. The energy resolution of the excitation light is $\simeq 15$ meV and the power always ranges between 50 and 100 μW for a 15-mm^2 spot. The total current from the sample, or the total collected current on the grid, is measured by a picoammeter.

Four sample holders are mounted on a 360°-rotation and 50-mm-translation stage. The samples may be either heated or pressed against a finger which is cooled at 77 or at 30 K by helium circulation.[12] They are prepared according to the well-known procedure used to produce NEA on a GaAs surface.[11] Nevertheless,

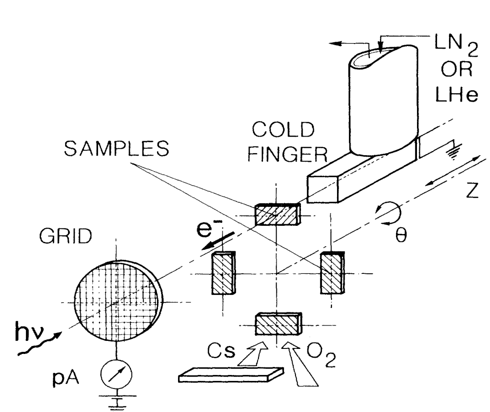

FIG. 1. Schematic sketch of the photoemission experiment. Four samples are on a rotation-translation (θ,Z) stage; they can be pressed against the finger which is cooled at 77 or at 30 K by helium circulation. Cesium adsorption is provided by the cesium dispenser, and oxygen by a microleak. The photoemitted current is collected on a positively biased grid.

because of the proximity of the layers to the surface, the samples are not etched, which might damage the quantum wells, and the heating temperature in vacuum is limited to 450°C to prevent destruction of the wells.[13] The pressure is kept in the low-10^{-10}-Torr range.

We have used two types of p-doped samples. The first one is a GaAs/GaAlAs SL and the second one a single GaAs/GaAlAs QW close to the surface.

Superlattice.—The sample contains a 750-period superlattice, 1200 Å from the GaAs surface (Fig. 2, upper part). The GaAs ($Ga_{1-x}Al_xAs$) layers are 52 Å (48 Å) thick and $x=32\%$. The SL is Be doped (3×10^{16} cm^{-3}) and the GaAs cap between the surface and the SL is 1×10^{19}-cm^{-3} Be doped. This sample was grown at AT&T Bell Laboratories (Murray Hill) by molecular beam epitaxy on a Zn-doped (100)-oriented GaAs substrate under As_2-rich growth conditions. Luminescence experiments were first performed to characterize the sample: From the excitation spectra at 1.7 K, we determined the energies of the E_{1h} (E_{1l}) optical transitions between the $n=1$ heavy (light) hole and conduction levels, and extrapolated these values for other temperatures. We obtained $E_{1h}=1.630$ eV, $E_{1l}=1.653$ eV at 1.7 K and $E_{1h}=1.534$ eV, $E_{1l}=1.557$ eV at room temperature.[14]

The photocurrent and its derivative are plotted in Fig. 2 as a function of the excitation light energy. The curves are similar to an excitation or absorption spectrum and can be analyzed in the same way. A step in the photocurrent labeled SL is observed at the energy of the E_{1h} transition. We analyze the curve as follows: (a) Between 1.4 eV (1.5 eV at $T=30$ K) and the SL step, the photoemitted current arises from excitation of electrons in the GaAs surface cap. The starting point of this curve is the same as for a GaAs sample (dashed curves), which means that our activation indeed produces a NEA surface. (b) The step SL is related to the superlattice: At $T=300$ K its energy is $E_{SL}=1.53$ eV, and at $T=30$ K we clearly resolve two structures which can be related to E_{1h} and E_{1l}. We measure their energies on the maxima of the derivative shown in the lower part of the figure, $E_{1h}=1.63$ eV and $E_{1l}=1.65$ eV. These results are in very good agreement with the luminescence studies and confirm the assignment of these structures to SL. We deduce an efficiency of the SL contribution to the photocurrent (in electron per incident photon) of 0.014% at 300 K, of 0.05% at 80 K, and of 0.07% at 30 K. Taking into account the reflection losses of 30% at the GaAs surface and the low absorption in the superlattice,[15] one obtains a yield (in photoemitted electron per promoted electron in the SL quantized conduction band) of 0.14% at 30 K. A lower activation temperature than for a GaAs sample may be a cause of decreased efficiency.

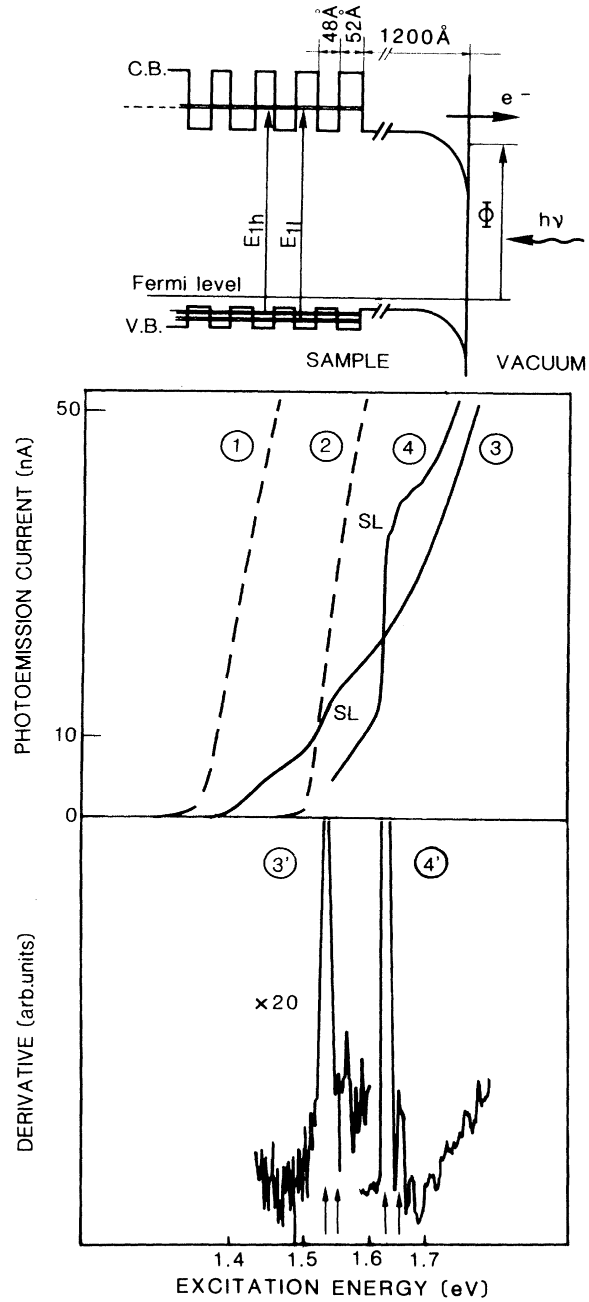

FIG. 2. Upper part: description in real space of the sample. E_{1h} and E_{1l} are the optically allowed transitions and Φ is the work function after activation to NEA. Lower part: photocurrent and its derivative. Curve 1 (2) is obtained on a bulk GaAs sample at 300 K (30 K); curve 3 (4), on the SL sample at 300 K (30 K). Curves 3′ and 4′ are the derivatives of 3 and 4. The arrows indicate the positions of the E_{1h} and E_{1l} transitions at 300 and 30 K.

The transport of electrons from localized states to the surface could be attributed to various mechanisms: (i) thermionic emission from the wells, which should disappear when the temperature is lowered, in contradiction with our results; (ii) defect-induced transport through the barriers, which would lead to very low efficiencies; and (iii) tunneling[16] through the $\simeq 40$-Å-thick barriers, an almost temperature-independent mechanism. We attribute the observed effect to (iii).

Quantum well.—The single QW is separated from the surface by a 30-Å-thick GaAs layer (Fig. 3, upper part). The thickness extrapolated from the growing rate of the GaAs QW's is 40 Å. The sample is p-type Mg doped ($\simeq 10^{18}$ cm^{-3}) to 500 Å from the surface. It was grown at Laboratoire d'Electronique et de Physique Appliquée by metalorganic chemical vapor phase deposition.

Typical 300-K results are presented in Fig. 3. The total photocurrent curve shows well-defined structures; their positions can be fitted with the calculated energies of the transitions between the quantized levels of the valence and conduction bands. The vertical bars in Fig. 3 indicate the calculated energy positions of E_{1h}, E_{1l}, and E_{2h} for a 40-Å-thick square QW and

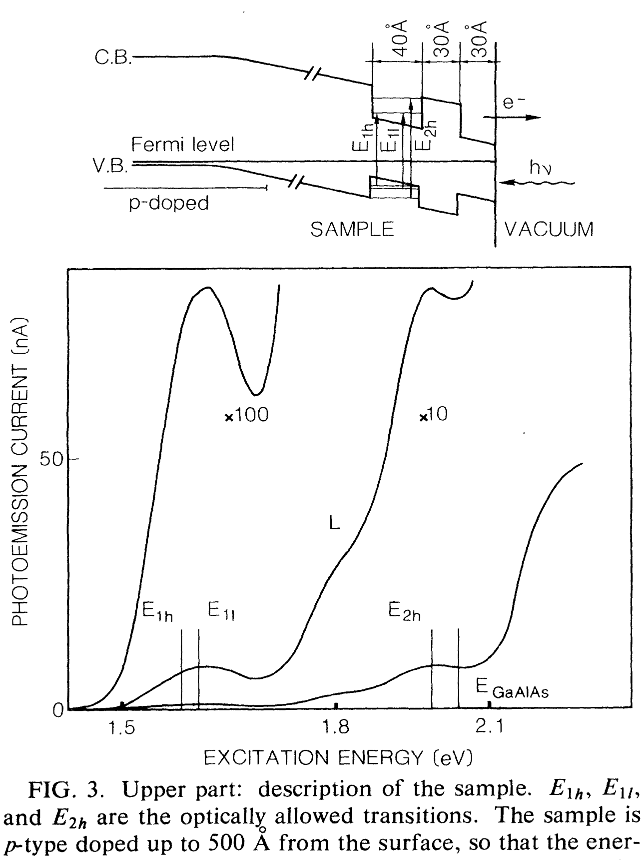

FIG. 3. Upper part: description of the sample. E_{1h}, E_{1l}, and E_{2h} are the optically allowed transitions. The sample is p-type doped up to 500 Å from the surface, so that the energy positions of the conduction and valence bands near the surface in the QW region vary linearly with the distance to the surface. Lower part: photocurrent at 300 K. The bars are located at the theoretical values of the optical transitions for a 40-Å-thick square QW.

the $Ga_{1-x}Al_xAs$ gap at 300 K for $x = 50\%$, $E_{GaAlAs} = 2.05$ eV ($E_{1h} = 1.574$ eV, $E_{1l} = 1.599$ eV, and $E_{2h} = 1.980$ eV),[17] in satisfactory agreement with the observed $n = 1$ and $n = 2$ transitions. To make sure of the relationship between these structures and the QW at the surface, we removed the QW by etching. After this treatment the structures at energies below the GaAlAs gap completely disappeared. The origin of the structure labeled L remains unclear. It may be due to photoemission from a quantized level in the L valley.

A precise analysis of the QW results is more difficult than for the SL case for several reasons: (a) Luminescence results at 1.7 K reveal a slight spatial inhomogeneity in the thickness of the layers. Yet their extrapolation to 300 K is in good agreement with the photoemission data. (b) The energy shift of the photoemission structure upon cooling is less than the expected value. This may be due to excitonic effects at low temperature. (c) The shape of the structure is somewhat sample dependent. (d) Furthermore, one could regard the GaAs layer at the surface as a QW, one wall of which is defined by the interface between the NEA solid and the vacuum; in this case a double QW should be considered. Nevertheless, a particular feature can be qualitatively understood: In Fig. 3 the E_{2h} transition is stronger than the E_{1h} one, in contrast to excitation or absorption experiments.[18] This confirms our interpretation of tunneling, which is easier for the $n = 2$ conduction level than for the deeper $n = 1$ level.

In conclusion, the present photoemission study gives evidence of the importance of electron tunneling through the GaAlAs barrier, leading to a photocurrent of 20 nA for an exciting power of 100 μW. A high luminescence polarization was observed in quantum structures[5,19] (50% instead of the maximum value of 25% in bulk GaAs) as a result of the lifting of the valence-band degeneracy between heavy and light holes. A large polarization of the emitted electrons is expected and an extension of the experiment for spin-polarization measurements is now under construction. These studies may lead to emission of intense electron beams into vacuum with polarizations much larger than the 50% limit obtained from bulk NEA GaAs.[20]

We thank R. C. Miller for consulting on the design of the superlattice structure and for preliminary optical measurement, and W. Wiegmann for molecular-beam-epitaxy sample growth.

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[14]In the envelope-function framework (see Ref. 3), the transitions for a 45-Å GaAs/50-Å GaAlAs SL may be calculated by use of either the "usual" or the "new" parameters as defined in R. C. Miller, D. A. Kleinman, and A. C. Gossard, Phys. Rev. B **29**, 7085 (1984). The usual (new) parameters lead to $E_{1h}=1.628$ eV (1.624 eV), $E_{1l}=1.643$ eV (1.655 eV) at 1.7 K. The present experiment cannot decide whether the conduction band offset $\Delta E_c = Q_c \Delta E_g$ corresponds to $Q_c = 0.85$ (usual) or $Q_c = 0.6$ (new).

[15]The absorption rate is 6×10^{-3} (1.2×10^{-3}) per transition and per well for the heavy (light) hole transition; see P. Voisin, in Proceedings of the Wigner School on Heterojunctions and Superlattices of Semiconductors, Les Houches, France (to be published).

[16]The same type of photoemission experiment is described in Ref. 9 but no structure related to localized states is reported. Moreover, the authors have looked for electrons escaping from the well at the bottom of the GaAlAs conduction band and have seemingly not considered the possibility of tunneling through a narrow barrier, as we do.

[17]These values are obtained with use of $Q_c = 0.85$ (see Ref. 14), whereas $Q_c = 0.6$ leads to $E_{1h}=1.569$ eV, $E_{1l}=1.618$ eV, and $E_{2h}=1.933$ eV.

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