PHYSICAL REVIEW B VOLUME 45, NUMBER 15 15 APRIL 1992-I

Tunneling spectroscopy of energy levels in wide quantum wells in tilted magnetic fields

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(Received 16 September 1991; revised manuscript received 5 December 1991)

Using resonant-tunneling spectroscopy, we have studied the energy levels in wide quantum wells (of 60 and 120 nm well width) of double-barrier resonant-tunneling devices in high magnetic fields with a small tilt angle α with respect to the growth axis. In the limit of high magnetic fields, the resonance spacing between successive levels becomes independent of the magnetic field and is $\cos^2\alpha$ times the spacing at zero field. In this limit, these results can be understood quasiclassically by considering the motion of the particles to follow the magnetic-field lines inside of a quantum well with an effective thickness $w/\cos\alpha$.

In this paper we report a spectroscopic study of energy levels in quantum wells in tilted magnetic fields. It is known from quantum-mechanical considerations that in wide quantum wells, at certain magnetic-field values there is a crossover between two-dimensional and three-dimensional cyclotron motion.[1] Such effects have been observed with luminescence measurement techniques[2] and are clearly visible in Shubnikov–de Haas oscillations in modulation-doped quantum wells.[3] Here, we observe this transition by means of resonant-tunneling spectroscopy.

In general the energy-level structure in quantum wells in a magnetic field, tilted at an angle α with respect to growth axis, is known to be very complicated, due to the mixing between the in-plane and the perpendicular motion. However, in the limit, where the size quantization can be treated as a perturbation, a very simple level structure results.[2,4] For example, it has been shown[5] that for a square quantum well of width w when $\lambda_B \ll w$ (λ_B being the magnetic length), the energy of the Landau levels of the lowest subbands depend on the total magnetic field and that levels from different subbands, with the same Landau level $N=0$, are described by

$$E_n(\alpha)=n^2\cos^2(\alpha)h^2/(8m^*w^2)\ , \tag{1}$$

where m^* is the effective mass and n the subband level number. This formula has a simple, appealing interpretation, namely that carriers move along the lines of the magnetic field and therefore cross the well at an angle α to the growth axis. Consequently they see an effectively wider quantum well of width $w/\cos\alpha$ and their size quantization energy diminishes correspondingly.

To study this effect we have measured the current-voltage $[I(V)]$ characteristic of double-barrier resonant-tunneling devices in a tilted magnetic field, in order to perform magnetotunneling spectroscopy.[6–8]

We have investigated two devices grown by molecular-beam epitaxy. Device (1) consists of the following layers in order of growth on a GaAs substrate ($n=2\times10^{18}$ cm^{-3}): 2-μm-thick GaAs buffer layer, $n=2\times10^{18}$ cm^{-3}; 50-nm GaAs, $n=2\times10^{16}$ cm^{-3}; 2.5-nm undoped GaAs layer; 5.6-nm undoped $Al_{0.4}Ga_{0.6}As$ barrier; 60-nm undoped GaAs well; 5.6-nm $Al_{0.4}Ga_{0.6}As$ barrier; 2.5-nm undoped GaAs layer; 50-nm GaAs, $n=2\times10^{16}$ cm^{-3}; 500-nm GaAs top contact layer, $n=2\times10^{18}$ cm^{-3}. The size of the mesas was 200×200 μm^2. Device (2) is identical except that the well width is 120 nm. The properties of these devices in zero magnetic field and with magnetic fields applied parallel and perpendicular to the growth axis have been described in recent publications.[9]

In Fig. 1 we show the position of the peaks in the $I(V)$ characteristic as a function of the magnetic field for a fixed tilt angle $\alpha=20°$ for device (1). At low voltages and high magnetic fields some structure is visible and the voltage of the peaks is independent of the magnetic field. Further structures at higher voltages do show a magnetic-field dependence. The inset of Fig. 1 shows the

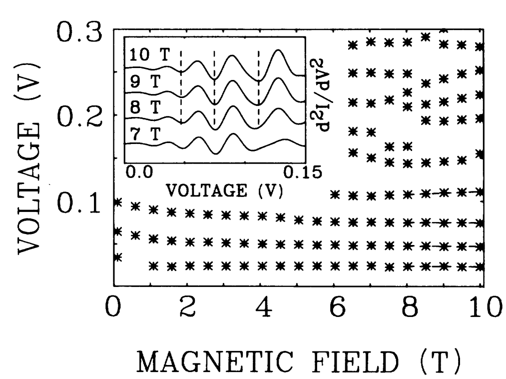

FIG. 1. Position of the maxima of the $I(V)$ characteristic as a function of the magnetic field at $\alpha=20°$ tilt angle. The lower-voltage peaks are independent of the magnetic field. The inset shows typical second derivatives of the $I(V)$ characteristic for various magnetic fields in the low-voltage region. The experiments have been performed at 4.2 K.

second derivative of the $I(V)$ characteristic for different values of the magnetic field. In order to understand these results we recall briefly the origin of the structure in the $I(V)$ characteristic. Maxima in the $I(V)$ characteristic correspond to voltages at which the voltage drop over the device leads to the alignment of the subbands in the emitter with the size-quantized levels in the well (resonant tunneling).[10] In the tunneling process the momentum perpendicular to the tunneling direction is conserved. Therefore, each peak in the $I(V)$ characteristic at zero magnetic field corresponds to the tunneling into a size-quantized subband. Since these subbands are closely spaced in a wide quantum well, a very rich structure is observed. In a tilted magnetic field the emitter states are quantized into Landau levels and, since the emitter may be considered to be three dimensional at low bias voltages, the Landau-level spacing is governed by the total magnetic field. When a magnetic field is applied parallel to the growth axis the rule of perpendicular momentum conservation is replaced by that of the conservation of the Landau-level index. On the basis of earlier experiments on the samples it is known that in the interesting field range (≈ 10 T) only the lowest Landau level ($N=0$) in the emitter is occupied.[9] Since the peaks in the $I(V)$ characteristic always occur at the same voltage, irrespective of the magnetic field, we conclude that electrons tunnel from the $N=0$ level in the emitter to an $N=0$ level in the well which, therefore, must have exactly the same field dependence as the emitter level. As there are several of these field-independent peaks, there must be several $N=0$ Landau levels in the quantum well.

There are extrema in the $I(V)$ characteristic which are, in the high-field limit, independent of the magnetic field, and we can plot their voltage positions as a function of the tilt angle for the two studied devices (Fig. 2). For both devices the voltage position of the peaks decreases with the increasing tilt angle. This decrease is larger for the peaks at higher voltages than for the ones at lower voltages. At the highest voltages this dependence is less clear but at these higher voltages also the peak position is not field independent and we ignore these peaks for the moment. Since the peaks shift to lower voltages at higher tilt angles this implies that the size quantization energy is reduced at higher tilt angles.

Qualitatively these observations fit well with the theoretical arguments described in the introductory part of this paper. We have calculated the energy levels of the quantum well as a function of the applied bias voltage, taking into account a voltage drop over the emitter and collector region. By comparing the maxima in the $I(V)$ at $B=0$ T with the calculated energy levels, we can fit the voltage drop and assign the subband quantum number n to each of these peaks. Using this assignment we can calculate the angular dependence of each of the maxima with Eq. (1) (solid lines in Fig. 2). We have obtained good agreement for 5 and 9 current peaks in devices (1) and (2), respectively, for tilt angles up to 30°. Deviations between the theoretical expected curves and the measured peak positions can be seen for higher voltages, where the peaks are no longer magnetic-field independent. The behavior of the lower resonances is well described by the formula, thus confirming the simple classical idea that the carriers move in orbits along the magnetic-field lines and effectively come under the influence of a potential well with thickness $w/\cos\alpha$.

The previous description shows that the subband spacing in a magnetic field diminishes with increasing tilt angle. In this section we will discuss this result and show qualitatively how it can be reconciled with existing

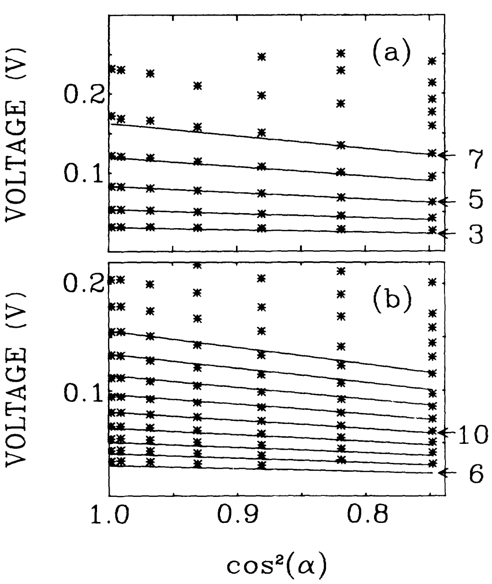

FIG. 2. Peak position in the $I(V)$ characteristic as a function of $\cos^2\alpha$ at 10 T for (a) device (1) and (b) device (2). The asterisks show the measured peaks and the solid line the theoretically calculated curve [$V_n(\alpha)=V_n(0)\cos^2\alpha$; V_n being the resonance voltage].

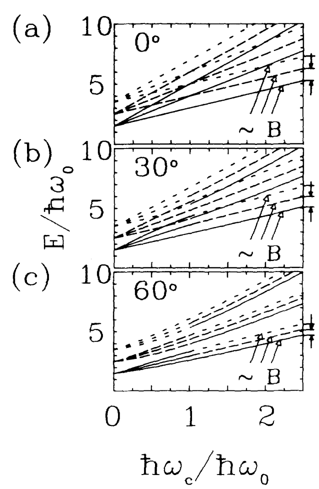

FIG. 3. Energy-level structure (Ref. 1) of a parabolic well [$V(z)=Cz^2$], as a function of the magnetic field [$\hbar\omega_c=\hbar eB/m^*$ and $\hbar\omega_0=\hbar(2C/m^*)^{12}$]. The energy difference between the lowest subbands in the high-field limit is indicated on the right-hand side of the figure. The slope of the energy levels, which is proportional to the total magnetic field **B**, is also indicated (only three electronic subbands with three respective Landau levels are shown).

theory of size-quantized states in tilted fields. For this purpose we calculate the energy levels of a quantum well with a parabolic potential profile in tilted magnetic fields since, for this particular potential shape, the energy-level structure can be completely solved analytically.[1,11] For zero tilt angles, where only the magnetic-field component parallel to the growth axis B_z is not zero, the levels consist of the electronic subbands with their Landau levels [Fig. 3(a)]. The crossover from the parallel to the perpendicular magnetic-field case is accomplished by the formation of anticrossings between the different subbands and their Landau levels [Figs. 3(a)–3(c)]. The interesting region is the high magnetic-field regime, where the level spacing of the lowest three levels is proportional to $\cos\alpha$ (Ref. 3) (indicated by arrows in Fig. 3). The energy of these levels is proportional not only to the parallel magnetic field B_z, but to the total magnetic field **B** and a three-dimensional cyclotron motion is fully developed. These levels are analogous to closer-spaced electronic subbands with a respective $N=0$ Landau level. The different level spacing in the parabolic quantum well (proportional to $\cos\alpha$) and the wells of devices (1) and (2) (proportional to $\cos^2\alpha$) is a consequence of the different conduction-band profiles of the parabolic and the real quantum wells.

In summary, we have used resonant-tunneling spectroscopy to investigate the level structure of wide quantum wells. In the limit of high magnetic fields and small tilt angles α, the voltages, at which the lowest resonances in the $I(V)$ characteristic occur, become independent of the magnetic field and are scaled down by a factor of $\cos^2\alpha$ with respect to the zero-tilt-angle case. The measurements are in good agreement with the theoretically predicted behavior. To give a qualitative understanding of how the energy levels evolve as a function of the magnetic field and the tilt angle, the quantum well is compared with a parabolic quantum well, where the energies can be calculated analytically.

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