Electron Transport in Kinetic Heterostructures

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The scope of this project is the investigation of heterostructures with large differences between the effective masses in the corresponding semiconductor materials. In 2001, mainly samples based on the InAs-GaAs material system were investigated, since our MBE for Sb based heterostructures was not yet operational. The masses in InAs and GaAs differ by a factor of three. The first samples we investigated were InAs self assembled dots and wetting layers since these sample are also interesting for various other applications in our institute. For our investigations, we employ Ballistic Electron Emission Microscopy (BEEM), a method which provides spectroscopic information on ballistic electron transport with nm spatial resolution.

Figure 1 (a) shows a sketch of the experimental setup and the cross-section view of the sample. The corresponding conduction band profile is shown in Fig. 1 (b). If the bias between the tip and the Au-base layer is large enough, ballistic electrons penetrating into the semiconductor can overcome the barrier at the InAs/GaAs interface and are collected at the collector contact. The corresponding current I_c as a function of bias V_t is called BEEM spectrum. The barrier height V_b is directly determined from the bias position of the current onset.

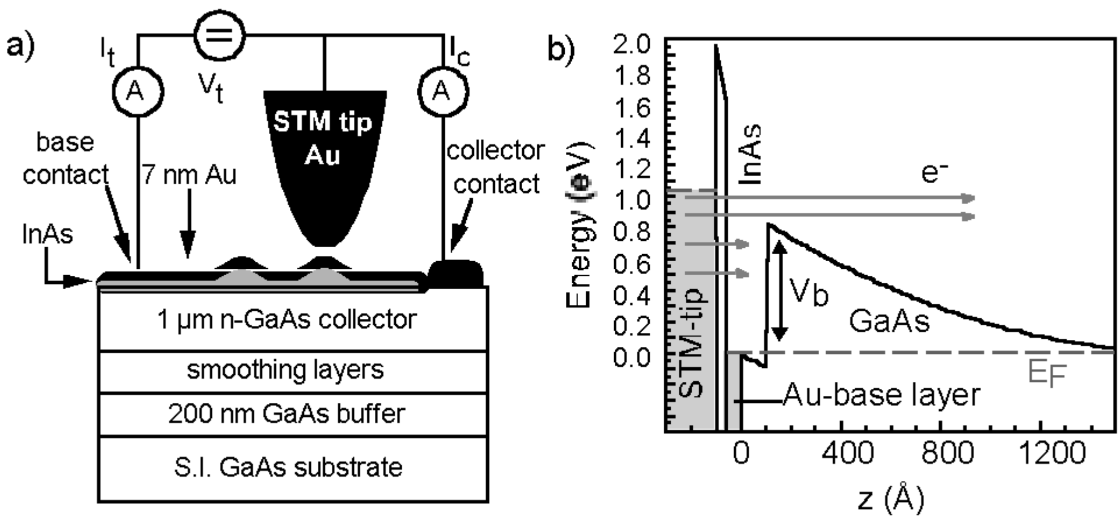

Fig. 1: Principle of BEEM operation. a) experimental setup, b) corresponding conduction band profile of our sample. V_t is the tunneling voltage, I_t the tunneling current, I_c the collector current (BEE current), E_F the Fermi energy, and V_b is the barrier height at the InAs-GaAs interface.

Figure 2 (a) shows a topographic STM (scanning tunneling microscope) image of our quantum dot sample. One small and three big dots are clearly visible. The granular structure in this image is due to the Au film covering the sample. Figure 2 (b) shows the corresponding BEEM image. Here the dots are visible as brighter spots indicating areas of enhanced electron transmission. Due to the influence of the wetting layer, the contrast between the on-dot and off-dot regions is rather weak.

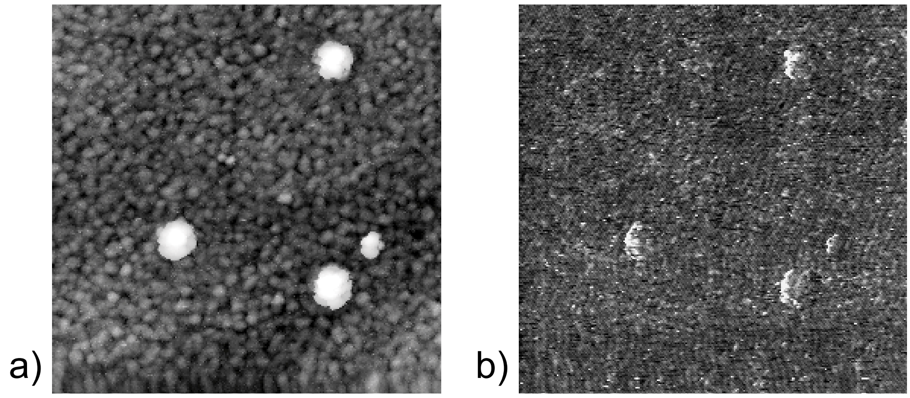

Fig. 2: a) STM topographic image of our sample, (scan size: 500 nm x 500 nm, V_t = 1.3 V, I_t = 2 nA). One small and three big dots are clearly visible. The granular structure in this image is due to the Au film covering the sample. b) corresponding BEEM image. The weak contrast is due to the wetting layer.

To investigate the contrast mechanism in more detail, BEEM spectra were measured on the dots and also at off-dot positions. Figure 3 shows a typical example of two BEEM spectra at T = 300 K, one measured on a dot and the other one measured in some distance from the dot. Already from the raw data one can clearly see that the onset voltage on the dot is strongly reduced compared to the off-dot onset voltage, which in turn is smaller than the value expected for a Au/GaAs Schottky contact (0.9 V). The barrier height gained from the power law fit is 0.69 eV and 0.80 eV for the on-dot and the off-dot position respectively. Further measurements at other positions on the sample show that at 300 K the barrier height on the dots is in general between 0.61 eV and 0.74 eV (mean value 0.69 eV), while for off-dot locations it varies from 0.73 eV to 0.87 eV (mean value 0.80 eV).

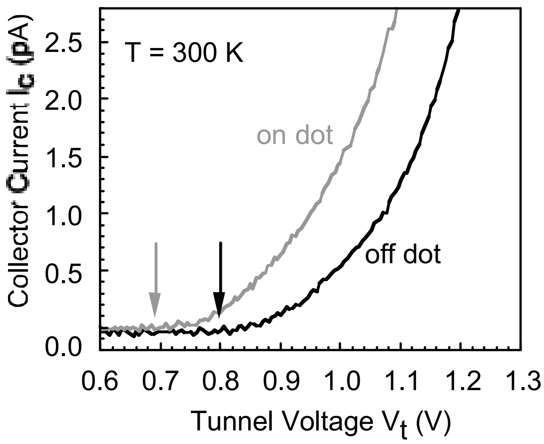

Fig. 3: Typical BEEM spectra measured on an InAs dot and in an off-dot region (I_t = 2 nA, T = 300 K).

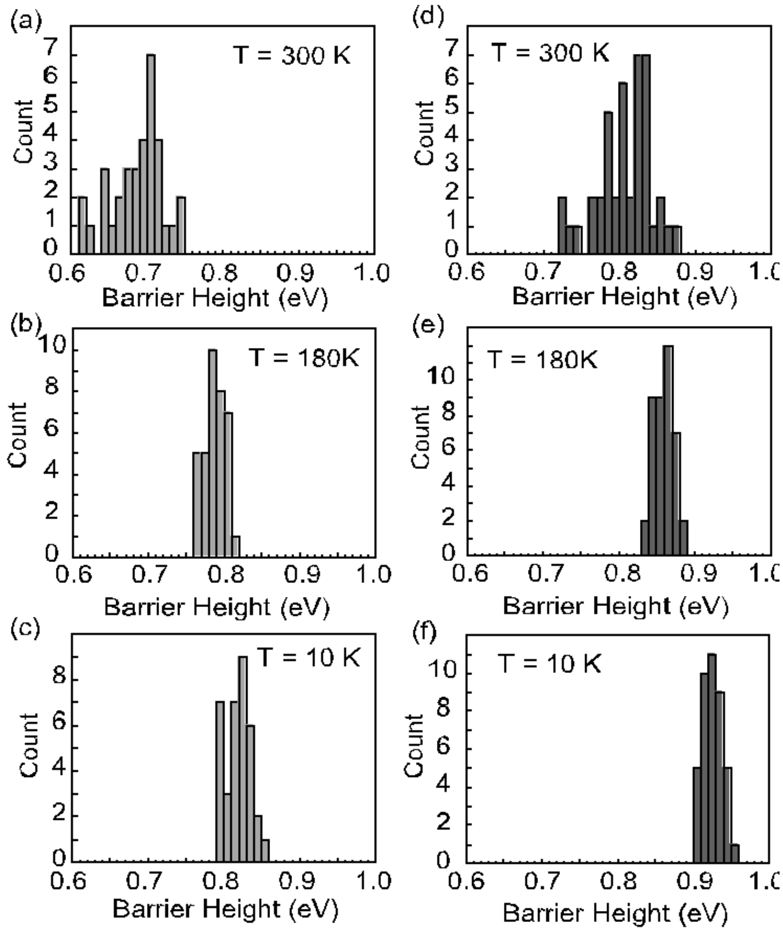

Fig. 4: (a – c) Histograms of the InAs/GaAs barrier heights measured on quantum dots at temperatures of 300 K, 180 K and 10 K, respectively. (d – f) Histograms of the barrier heights between the InAs wetting layer and the GaAs measured in off-dot regions at temperatures of 300 K, 180 K and 10 K, respectively.

To investigate the InAs/GaAs barrier height in dependence of the temperature we also sampled BEEM curves on various on-dot and off-dot positions at 180 K and 10 K, respectively. As can be seen from Fig. 4, the measurements show an increase in barrier height with decreasing temperature both for the on-dot positions and the wetting layer. On the dots (a – c), the mean value of the barrier height rises from 0.69 eV (standard deviation 34 meV) to 0.79 eV (standard deviation 13 meV) between T = 300 K and T = 180 K. A further lowering of the temperature down to 10 K results just in a slightly higher mean barrier height of 0.82 eV (standard deviation 16 meV). Note that the distribution of the barrier height becomes significantly narrower between T = 300 K and T = 180 K but approximately maintains its width when the temperature is further reduced. In our opinion this behavior is mainly due to the reduction of drift problems with decreasing temperature. On the wetting layer (Fig. 4 (d – f)) the mean value of the barrier height rises from 0.80 eV (standard deviation 35 meV) at T = 300 K to 0.86 eV (standard deviation 12 meV) at T = 180 K and to 0.93 eV (standard deviation 13 meV) at T = 10 K.

It is quite instructive to compare our results with BEEM measurements on an Au-InAs-GaAs system with homogeneous InAs interlayers of various thickness, carried out by Mao-Long Ke et al. [1].

They report that, at T = 300 K, a single monolayer of InAs lowers the barrier height rapidly from 0.9 eV to 0.8 eV, while an increase of the nominal InAs layer thickness to 3 monolayers yields a further decrease to approximately 0.74 eV. For thicker layers the barrier height remains almost constant up to 27 monolayers, where it drops again and finally reaches ≈0.63 eV for a thickness of 33 monolayers (≈11 nm) and beyond. These data indicate that the average thickness of our wetting layer is about one monolayer, while our dots are on average approximately 30 monolayers thick and the large dots appear to have a thickness of more than 33 monolayers. This result agrees very well with the dot height gained from AFM measurements. Of course one must bear in mind that the data from Ke et al. were obtained on homogeneous InAs layers rather than on InAs dots. In contrast to a partially strain-relaxed system of SAQDs on a wetting layer, thin homogeneous InAs layers are fully strained and thick homogeneous InAs layers are strain-relaxed via dislocations. The different strain conditions for the two systems most probably influence the barrier height.

In summary, we have used BEEM/S to study InAs self assembled quantum dots on a GaAs substrate. It is found that in first approximation the barrier height between the quantum dots and the GaAs behaves similar to that of homogeneous InAs layers on GaAs reported in the literature. On the basis of these results, our data suggest a thickness of one monolayer for the wetting layer and a thickness of 30 monolayers and more for the dots, which is in excellent agreement with results from AFM measurements. Furthermore, a significant increase of the barrier height for lower temperatures is observed. The complex influence of both geometry factors and temperature on the InAs-GaAs barrier height and, therefore, on the energy levels inside of InAs quantum dots will make bandstructure engineering for quantum dot applications a quite difficult task.

Reference

[1] Mao-Long Ke, D.I. Westwood, C.C. Matthai, B.E. Richardson, and R.H. Williams, J. Vac. Sci. Technol. B **14(4)**, 2786 (1996).