BEEM/BEES Investigations on AlAs/GaAs Single Barriers and RTDs

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Ballistic Electron Emission Microscopy/Spectroscopy (BEEM/S) [1], a three terminal extension of Scanning Tunneling Microscopy (STM), was used for the local investigation of electrical properties of semiconductor heterostructures. In BEEM/S an STM tip is used to inject hot (ballistic) electrons into a semiconductor via a thin metallic base layer. The resulting ballistic current can be measured on the backside of the sample via a collector contact. Therefore, BEEM/S is, in contrast to STM, able to probe also sub-surface structures with a local resolution of several nanometers.

In this work we present results of BEEM/S on MBE grown AlAs-GaAs double barrier resonant tunneling diodes (DBRTDs) and AlAs single barriers on a GaAs substrate. As a base layer we used in all cases a 7 nm thick, polycrystalline Au layer. The measurements presented here were all carried out at cryogenic temperatures (either 4.2 K or 10 K).

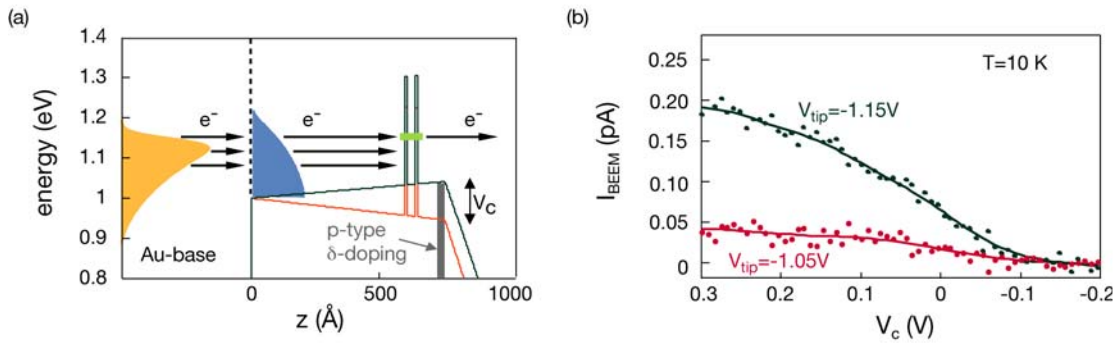

Fig. 1: (a) Band profile of the sample used for the electron refraction measurement, sketched for the unbiased sample and for a positive collector voltage, which lowers the band profile. Also indicated are the electron energy distribution in the Au base layer and the one in the GaAs, showing the massive broadening caused by the refraction.
(b) Measured electron energy distribution in the GaAs for two different tunnel voltages.

An important effect influencing the ballistic current on e.g. Au-GaAs samples is the "refraction", which the ballistic electrons experience at the Au-GaAs interface. For electrons crossing this interface ballistically, the momentum parallel to the interface is conserved. Thus, a change in effective mass and/or potential leads to "electron refraction effects", which have a significant influence on the BEE spectra. For example, the expected step-like spectrum of a single resonant level in a heterostructure is turned into a linear rise, which is well-known from the BEE spectra of various DBRTDs. Although the effect on the BEE spectra has been demonstrated repeatedly, up to now a direct measurement of the ballistic electron distribution beyond the Au-GaAs interface was, due to various technical problems, missing. To achieve this measurement, we designed a heterostructure with a buried AlAs-GaAs-AlAs-DBRTD and a p-δ-doping (see Fig. 1 (a)). This sample design enabled us to apply a bias voltage between the Au-base and the collector. With a slightly modified BEEM setup we were then able to map directly the energetic distribution of the ballistic electrons in the GaAs by measuring the ballistic current as a function of the sample bias Vc (see Fig.1 (b)), i.e. using the RTD as a tunable energy filter for the ballistic electrons. This measurement confirmed that, in agreement with theory, the refraction leads to a considerable broadening in the energetic distribution of the injected electrons [2].

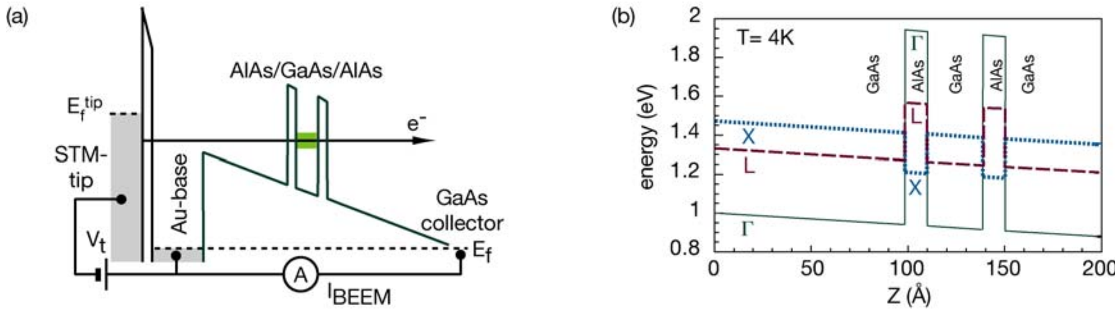

Fig. 2: (a) Sketch of the setup together with the Γ-band profile of a 30Å wide RTD sample, also indicating the position of the resonant level.
(b) Close-up view on the RTD, showing besides the Γ- also the X- and the L-valley band profile.

In order to investigate higher conduction bands, we demonstrated ballistic transport through confined states in the L-valley of an AlAs-GaAs-AlAs DBRTD [3]. In contrast to so-called “3-terminal-devices”, a solid state device designed for ballistic transport, BEEM/S is capable of injecting electrons into the L-valley coherently because of the broad momentum distribution in the metallic base layer. The ballistic spectra of the DBRTDs studied (see Fig. 2) show a first onset followed by a pronounced linear regime caused by the first resonant level in the Γ-valley of the DBRTD. Tunneling processes through the L-valley confined states of the DBRTD are observed as additional current onsets (well above the onset caused by the resonant level in the Γ-valley) followed by a very short linear regime (see Fig. 3). These features can be seen more clearly in the first derivative of the ballistic current. Using DBRTDs of different well width (20 Å, 30 Å, 40 Å), we confirmed that the additional onset is dependent on the well width and therefore due to a resonant level in the RTD rather than to a simple barrier overshoot in a higher valley. Measurements on a reference sample with a single AlAs barrier (100 Å thick) show that at cryogenic temperatures the Γ-X-transfer can also be neglected. Finally, the design of our DBRTD rules out any influence of a higher resonant level in the Γ-valley, because the second resonant level in Γ is well above the onset position observed. Therefore, we conclude that we truly observed tunneling through a resonant level in the L-valley. This is further confirmed by the results of a semiempirical tight binding calculation which reproduces the experimental data very well. This calculation can furthermore be used to derive the corresponding ballistic transport mass. As a result, we found that this ballistic transport mass differs significantly from the GaAs and AlAs longitudinal and transversal masses, which is due to the mass anisotropy in the L-valley. Using the ballistic transport mass derived by the tight-binding model as an input parameter, the experimental data can also be reproduced very well with a simple effective mass model.

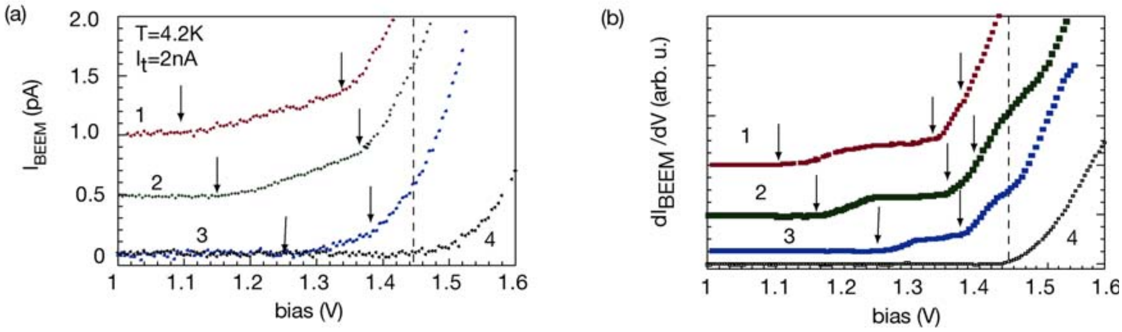

Fig. 3: (a) Measured BEEM spectra. Curves 1–3: RTDs with 40 Å, 30 Å, and 20 Å well width respectively. Curve 4: 100 Å thick AlAs single barrier. The arrows indicate the positions of the resonant levels; the dashed line marks the X-valley at the Au-GaAs interface.
(b) First derivative of the spectra shown in (a).

On single AlAs barriers we investigate the local influence of doping on the band structure [4]. For this purpose several, otherwise identical, samples were grown, each having a 100Å thick, single AlAs barrier with a specific donor concentration in the barrier. Up to now we have investigated barriers with doping concentrations of 1e17 cm^{-3}, 3e16 cm^{-3}, and an undoped reference sample. We observe that the onset voltage in the ballistic spectra shifts for higher doping concentrations to lower values. By taking BEEM images of the different samples, an even more direct approach to show the influence of the doping atoms on the band structure was also pursued. Images depict a quite uniform "potential landscape" for the undoped as well as for the highly doped sample. On the other hand, the samples with a doping of 3e16 cm^{-3} reveal a higher inhomogeneity in the BEEM images, which may be a signature of single impurities (Fig. 4).

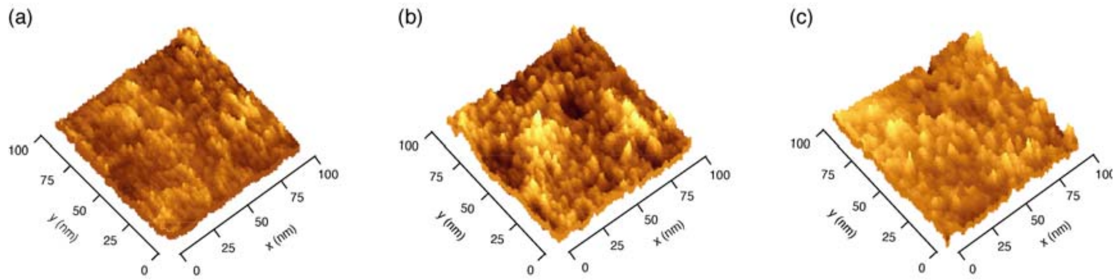

Fig. 4: BEEM images for AlAs single barriers with different doping concentrations.
(a) undoped barrier, (b) N_D = 3e16 cm^{-3}, (c) N_D = 1e17 cm^{-3}.

References:

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