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Magnetic field effects and $k_{\|}$-filtering in BEEM on GaAs-AlGaAs resonant tunneling structures

J. Smoliner[1,*], **R. Heer**[1], **G. Strasser**[1], **C. Strahberger**[2]

[1] Institut für Festkörperelektronik und Mikrostrukturzentrum der TU-Wien, Floragasse 7, 1040 Wien, Austria
[2] Walter Schottky Institut, TU-München, Am Coulombwall, 85748 Garching, Germany

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Abstract. In this work, GaAs-AlGaAs double barrier resonant tunneling diodes (RTDs) are investigated by ballistic electron emission microscopy (BEEM). RTDs grown directly below the sample surface exhibit characteristic steplike features in the BEEM spectrum, whereas for buried RTDs, a linear spectrum is observed. Moreover, the BEEM spectra of sub-surface RTDs show Shubnikov-de Haas-like oscillations in magnetic fields.

To investigate the origin of these effects, the BEEM spectra were calculated using a scattering formalism within the framework of a semi-empirical tight binding method. As a main result we found that, independent of the applied bias, only electrons within a narrow $k_{\|}$ distribution are transferred resonantly through the RTD. Hence, a $k_{\|}$ filter is established for ballistic electrons close to $k_{\|} = 0$. The calculated filter width is consistent with the magnetic field data.

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Ballistic electron emission microscopy (BEEM) [1, 2] is a three terminal extension of scanning tunneling microscopy (STM), where hot electrons are injected into a semiconductor via a thin metallic base layer. Originally used to determine Schottky barrier heights [3–6], BEEM is now frequently used to study buried interfaces in semiconductor heterostructures [7]. Misfit dislocations [8] on buried InGaAs-GaAs interfaces have been investigated by BEEM instead of cathodoluminescense experiments, which were traditionally used for this purpose. Besides structural properties of buried interfaces, interface bandstructure effects have also been investigated. Good examples of such an experiment are the determination of the GaAs-AlGaAs band offsets as a function of aluminum concentration [9] and the determination of the energetic position of higher conduction bands in AlAs [10].

Size quantized states such as resonant levels in GaAs-AlGaAs resonant tunneling diodes (RTDs) [11] and minibands in superlattices have also been investigated by BEEM. On GaAs-AlGaAs superlattices, the BEEM signal was found to be larger than on GaAs-AlGaAs RTDs due to the broad transmission range of the superlattice miniband. By applying an external bias between the base and the collector of such samples, the superlattice was employed as tunable energy filter and the energetic distribution of ballistic electrons was determined [12, 13].

In our recent work, GaAs-AlGaAs resonant tunneling structures were studied. A characteristic steplike feature was observed in the BEEM spectra of samples where the RTD was located directly below the metal base layer [14]. However, for buried RTDs, an almost linear spectrum was observed. In terms of a Bell-Kaiser model it was found that these structures can be considered as parallel momentum filter [14] for electrons close to $k_{\|} = 0$.

In this work, low temperature BEEM studies in strong magnetic fields are reported for such samples as described above. Measured as a function of the magnetic field applied parallel to the tunneling current, the BEEM current of a sub-surface RTD shows a Shubnikov-de Haas-like oscillating behavior. Using advanced simulation methods within the framework of a semi-empirical tight binding method, the microscopic origin of this effect is explained and the width of the wave vector filter is determined.

1 Experimental setup

For the present experiment, molecular beam epitaxy (MBE) grown GaAs-AlGaAs double barrier RTDs were used. The samples were grown in the following way: On a semi-insulating substrate, an n-doped GaAs collector region ($d = 1\ \mu$m, $N_D = 1 \times 10^{18}\ cm^{-3}$) layer was grown, followed by a layer of 1500 Å undoped GaAs to provide a high internal sample resistance. On top of this layer, a double barrier RTD and a very thin protecting GaAs cap layer were grown. The AlGaAs barriers had a thickness of 37 Å ($x = 0.4$).

*Corresponding author. (E-mail: juergen.smoliner@tuwien.ac.at)

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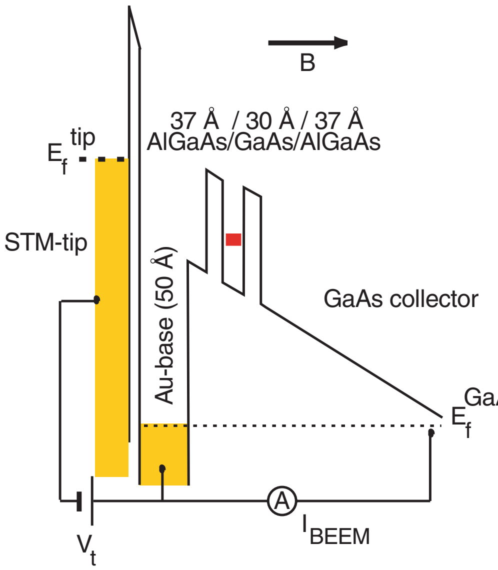

Fig. 1. Overview of the experimental setup together with a schematic conduction band profile of our sample. The direction of the magnetic field and the resonant level inside the resonant tunneling structure are also indicated

The GaAs well between the barriers was 30 Å wide. A plot of the conduction band profile is shown in Fig. 1 together with a schematic of the experiment. The samples were designed so that just one resonant level exists within the AlGaAs barriers.

To prepare the samples for BEEM, an In/Sn collector contact was first alloyed in forming gas atmosphere. Then the samples were dipped into HCl (35%) to remove the native thin oxide layer. Finally an Au film (75 Å) was evaporated via a shadow mask. The size of the active area was $0.2\,\text{mm} \times 3\,\text{mm}$. All measurements were carried out at a temperature of $T = 4.2\,\text{K}$ and a tunneling current of 5 nA.

2 Results and discussion

Figure 2a shows typical BEEM spectra measured at various magnetic fields. Several features are evident: At $B = 0\,\text{T}$ (curve 1), the BEEM current is zero below V_t (tunneling bias) $= 1.05\,\text{V}$, which corresponds to the situation where the Fermi level in the tip is aligned with the resonant level inside the double barrier structure. Between $V_t = 1.05\,\text{V}$ and $V_t = 1.25\,\text{V}$, i.e., the Fermi level in the tip remains below the AlGaAs barrier height, a steplike feature is observed. For higher bias values, the barrier height is overcome and the ballistic current increases strongly.

With increasing magnetic field, the spectral behavior appears to be unsystematic. To illustrate this, three typical curves for high magnetic fields are shown. At $B = 2.6\,\text{T}$ (curve 2), the steplike feature disappears and the current is always smaller than that at zero magnetic field. At $B = 3\,\text{T}$ (curve 3), the step is well pronounced again and the BEEM current is enhanced compared to the $B = 0\,\text{T}$ spectrum. At $B = 8.15\,\text{T}$ (curve 4), the step is weak and the ballistic current is generally reduced compared to the $B = 0\,\text{T}$ spectrum but larger than that for the $B = 2.6\,\text{T}$ spectrum. In addition, the step is shifted to higher bias. Note that this influence of the magnetic field is only observed at liquid helium temperatures. At $T = 100\,\text{K}$, the BEEM spectra no longer change with increasing magnetic field.

The BEEM current was also investigated as a function of magnetic field, keeping V_t constant. For this purpose, a set of BEEM spectra was measured at various magnetic fields, keeping B constant during the measurement. This procedure was chosen because the tip position is drifting in magnetic fields due to magnetostriction effects in the scanning piezo. To make sure that all spectra were measured at the same position, images were taken before each spectrum. The tip position was then corrected manually, taking a prominent topographic structure as reference point.

In Fig. 2b, the BEEM current is plotted as function of the magnetic field for $V_t = 1.25\,\text{V}$ (curve 1) and $V_t = 1.15\,\text{V}$ (curve 2). As one can see, the data exhibit an oscillatory behavior, and the most pronounced minima are marked by arrows. By comparing the two curves, it is obvious that all minima positions are shifted if the STM bias is changed and the shift increases with increasing magnetic field. The bias dependence of the minima positions immediately explains the apparently unsystematic B-dependent behavior of the BEEM spectra. Each point of the BEEM spectrum oscillates at its

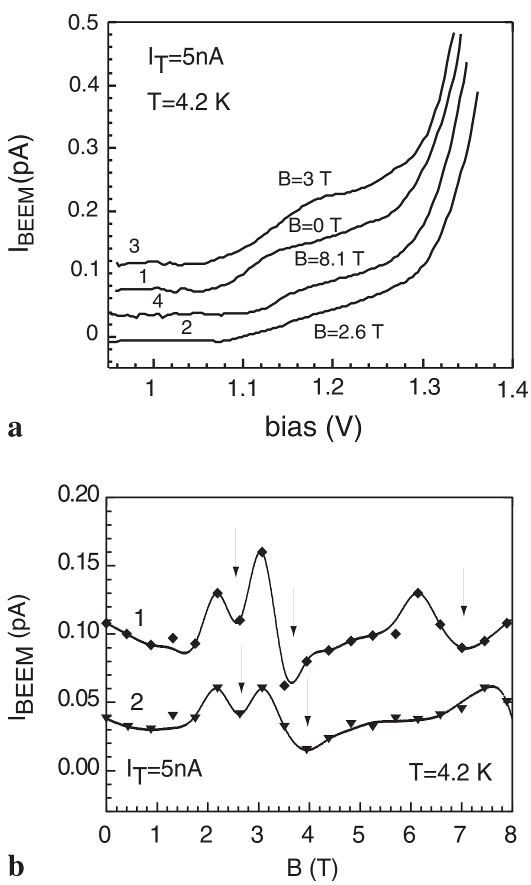

Fig. 2. **a** BEEM spectra recorded at magnetic fields of $B = 0\,\text{T}$ (*curve 1*), $B = 2.6\,\text{T}$ (*curve 2*), $B = 3\,\text{T}$ (*curve 3*) and $B = 8.16\,\text{T}$ (*curve 4*), respectively. All measurements were carried out at $T = 4.2\,\text{K}$ and a tunneling current of 5 nA. An offset was added to the spectra for better clarity. **b** BEEM current as a function of magnetic field for a STM bias of $V_t = 1.25\,\text{V}$ (*curve 1*) and $V_t = 1.15\,\text{V}$ (*curve 2*). The *solid lines* are just a guide to the eye; the *arrows* mark the positions of the minima

own frequency in B, and therefore no obvious magnetic field dependence can be directly observed in the spectra.

In our previous work [14] we have shown experimentally, that sub-surface RTDs can be considered as a momentum filter for electrons around $k_{\parallel} = 0$. In other words, only electrons around $E_{\parallel} \approx 0$ can be transmitted resonantly, where

$$E_{\parallel} = \frac{\hbar^2 k_{\parallel}^2}{2m^*}$$

denotes the energy component parallel to the barriers. This behavior explains the steplike features in the BEEM spectra as well as the observed magnetic field dependence. As long as the Fermi energy in the tip is below the AlGaAs barrier height, a constant number of electrons will tunnel resonantly; this is because the allowed energy regime for resonant tunneling is always the same in $E_{\parallel}$ and $E_{\perp}$, independent of what the Fermi energy in the tip is. Thus, the corresponding BEEM current stays constant in this regime.

The oscillatory behavior of the BEEM spectra in magnetic fields can be explained in analogy to the Shubnikov-de Haas effect in two-dimensional electron gas systems. In magnetic fields, Landau levels will exist inside the RTD. If the magnetic field is increased, the Landau level spacing also increases. Thus, the number of Landau levels inside the allowed $E_{\parallel}$ range will decrease. As each allowed Landau level carries a part of the BEEM current, a minimum in the BEEM current can be expected each time a Landau level is shifted outside the allowed $E_{\parallel}$ range. The minima will be equidistant in $1/B$, and in analogy to the Shubnikov-de Haas effect, the width of the allowed $E_{\parallel}$ range is determined by

$$\Delta E_{\parallel} = \frac{\hbar}{m^* \Delta(1/B)} ,$$

where $m^* = 0.067 m_0$ is the effective mass of GaAs, and $\Delta(1/B) = (1/B_n - 1/B_{n+1})$ is the distance between two adjacent minima in the BEEM current as a function of the magnetic field.

If we look at the data in Fig. 2b, we observe three clear minima for the curve obtained at $V_t = 1.25$ V and two minima for the curve obtained at $V_t = 1.15$ V. Inserting the minima position in the above relation yields a filter width of $\Delta E_{\parallel}(1.25\,\text{V}) = 13$ meV and $\Delta E_{\parallel}(1.15\,\text{V}) = 11$ meV. This indicates that the filter width increases with increasing STM bias, and a detailed analysis of $\Delta E_{\parallel}$ as a function of V_t will be the subject of future investigations.

In our previous work [14] the $k_{\parallel}$ filtering effect was explained by qualitative arguments within the framework of the commonly accepted Bell-Kaiser model. Using $\Delta E_{\parallel}$ as a fitting parameter for the border of integration over $E_{\parallel}$, excellent agreement between the measured and calculated spectra could be achieved. However, the microscopic origin of the $k_{\parallel}$ filtering effect could not be explained in terms of this simple model. To clarify this, more advanced model calculations were employed, which are outlined below.

The small distance between the resonant state inside the RTD and the sample surface suggests that some interplay of surface related effects and the resonant level might be responsible for the fact that steps in the BEEM spectrum are observed for the sub-surface RTDs but not for buried structures. Among other investigations, BEEM studies [15, 16] have shown that Au-GaAs interfaces are not perfect, and even at room temperature, Au diffuses quickly more than two monolayers deep in the sample [17, 18]. Moreover, an outdiffusion of Ga or As atoms into the gold can occur so that a considerable amount of disorder can be expected at the Au-GaAs interface. To calculate the BEEM spectrum for such a disordered interface, a scattering formalism within the framework of semi-empirical tight binding was employed. For the simulation of a disordered interface a 2×2 (8 Å × 8 Å) lateral super-cell was used. The Au atoms were placed randomly in interstitial sites of the first 5 Å of the GaAs cap layer. The results were checked for independence from the exact arrangement of the Au atoms. Qualitatively very similar results emerge from other geometries of the lateral super-cell (e.g. 12 Å × 4 Å). This enabled us to incorporate the position of every single atom and to obtain a realistic description of the electronic structure of our sample. As the "real" interface structure will always be unknown, we decided to use two monolayers of Au atoms on GaAs interstitial sites as a reasonably realistic model assumption for the interface. Several other interface geometries were also considered, and all led qualitatively to the same results. Further details of these simulations will be published elsewhere, since the calculations are computational expensive and still in progress.

Figure 3a shows a comparison between calculated BEEM spectra, where for the lower curve a perfect Au-GaAs interface and for the upper curve 2 monolayers of Au in GaAs interstitial sites were assumed. The surface barrier height at $T = 4.2$ K was determined to be 1.0 eV, which we also found in our previous experiments. The ballistic current is zero as long as the Fermi level in the tip is below the resonant level of the RTD, which is at 1.1 eV. In the regime where the Fermi level in the tip is above the resonant level but is below the AlGaAs barrier height, the BEEM spectrum is linear for a perfect interface, whereas the spectrum for the non-perfect interface exhibits a clear steplike feature. Note that the shape of the step is very sensitive to the distance between the surface and the RTD. For a distance of 4 nm, such as in our sample, the step in the spectrum is well pronounced; however, it is completely removed if a distance of 10 nm is assumed. This theoretical finding is in perfect agreement with reference measurements carried out on samples having the same RTD structure but a 10 nm cap layer, the BEEM data of which also exhibit a linear spectral behavior.

Figures 3b and c show the ballistic current distribution plotted as a function of $k_{\parallel}$, using V_t as a parameter (while the BEEM spectrum shown in Fig. 3a is simply the integral of these curves plotted as a function of V_t). For the bias range, we again consider the regime where the Fermi level in the tip is above the resonant level in the RTD but still below the AlGaAs barrier height. Figure 3b shows the results assuming a perfect interface, and Fig. 3c the results for two layers of Au in GaAs interstitial sites. For the perfect interface, the ballistic current has a maximum at $k_{\parallel} = 0$, then decreases slowly and drops sharply at $k_{\parallel}$ values which correspond to the border of the classical "acceptance cone" in BEEM experiments. The width of the peak increases with increasing bias, which is the reason

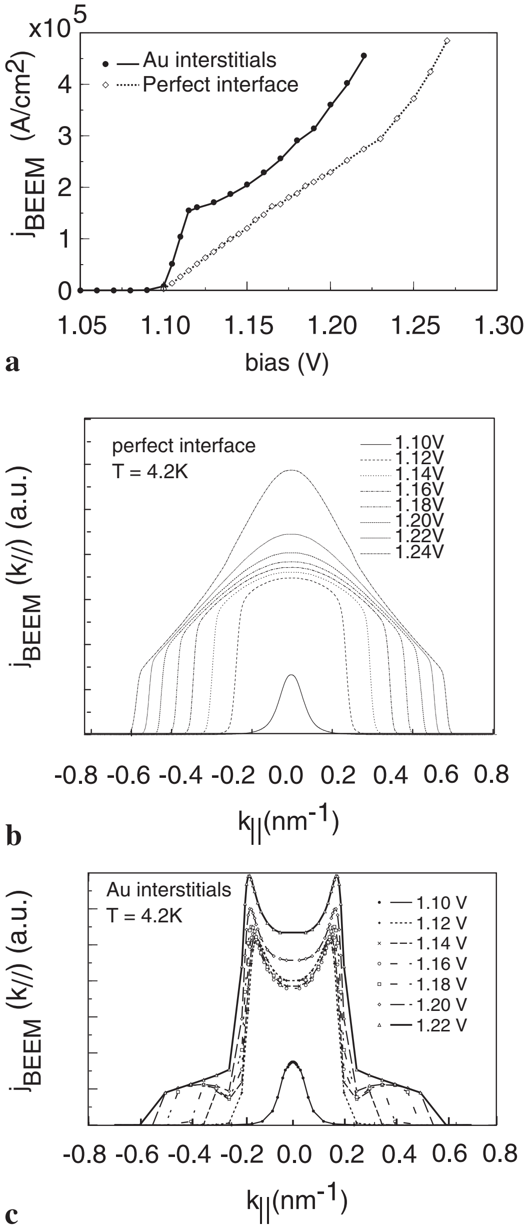

Fig. 3. a Calculated BEEM spectra for a perfect interface and an interface with two layers of Au atoms in interstitial positions. **b** Calculated BEEM current density as a function of $k_{\parallel}$ for V_t between 1.10 V and 1.22 V, assuming a perfect Au-GaAs interface. **c** same as **b** but for two layers of Au atoms in interstitial positions

why a linear spectrum is observed. The strongly increasing peak height at higher bias is due to the contribution of higher conduction bands in the GaAs. Just for reference purposes, the curve at a bias of 1.00 V shows the situation where the Fermi energy in the tip is still below the resonant level.

As one can see, the current distributions in Fig. 3c are substantially different. Here, the current maximum is not at $k_{\parallel} = 0$. Beyond this maximum, the current first drops sharply and then slowly goes to zero at the same positions as for the perfect interface. In contrast to the perfect interface, however, the width of the centerpeak is almost independent of bias, which is the reason why a step is observed in the corresponding BEEM spectrum. Most probably, this behavior is due to quantum interference effects in the region between the interface and the RTD, which is consistent with our experimental and theoretical findings that the step disappears if the distance between the surface and the RTD is increased. Finally, the width of the calculated current distribution can be compared with the values obtained from the magnetic field data. If we take the FWHM value for a bias of 1.14 V we obtain $k_{\parallel} = 0.17\,\text{nm}^{-1}$. This corresponds to an $E_{\parallel}$ of 16 meV, which is in reasonably good agreement with the experimental result of 11 meV at $V_t = 1.15$ V, especially if the simplicity of our model assumption is taken into account.

Taking the good agreement between the model calculation and the experimental data as an indication that our simplifying assumptions about the intermixed Au-Gas interface are reasonably realistic, we briefly discuss the prospects of our findings. The observed effects are obviously due to the interplay between the low-dimensional state inside the RTD and the modified crystal structure in front of the RTD. Until now, this situation has only been weakly explored, since most low-dimensional systems are realized on the basis of the GaAs-AlGaAs material system, where the crystal structure in both components is the same. Due to the tremendous advances in MBE growth, however, heterostructures containing low-dimensional states embedded between components with strongly different material parameters can now be fabricated in a controlled way. On such samples, effects such as those described above should be more pronounced, and in addition, new effects can be expected.

In summary, magnetic field dependent BEEM studies were carried out on GaAs-AlGaAs RTDs grown directly below the sample surface. Due to the small distance (4 nm) between the surface and the RTD, a steplike feature is observed in the BEEM spectra, which exhibits a Shubnikov-de Haas-like oscillating behavior in strong magnetic fields. Both the step and the magnetic field dependence are not observed for RTDs buried 10 nm below the surface. Using the framework of a tight binding model, we show that the observed effects can be explained by an interplay between the intermixed Au-GaAs interface and the resonant state inside the RTD. In this way, a parallel momentum filter for electrons around $k_{\parallel} = 0$ is established and a highly directed beam of electrons is injected into the semiconductor.

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