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Imaging of interference between incident and reflected electron waves at an InAs/GaSb heterointerface by low-temperature scanning tunneling spectroscopy

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1. Introduction

Electron transmission and reflection characteristics at semiconductor heterointerfaces govern the operation of heterostructure devices like tunneling transistors, in which current flows normal to the heterointerface. For most electric or optical measurements, however, it is impossible to investigate electronic behavior locally at nanometer-scale resolution and only statistical averages over large areas can be obtained. In particular for multilayer structures, it is difficult to obtain information concerning each heterointerface independently. Here, this limitation is overcome by investigating the electron transmission and reflection characteristics at one heterointerface by low-temperature scanning tunneling spectroscopy (LT-STS) on a cross sectional surface of a heterostructure. By measuring the STS spectra at each point while scanning the probe, the local electron density of states (LDOS), as a function of the electron energy, can be mapped in real space with nano-scale resolution [1].

2. Experimental procedures

The sample consisted of a GaSb(7 nm)/InAs(6 nm) superlattice (SL) on a thick InAs layer grown on an InAs substrate. All layers including the substrate were undoped. To obtain a clean cross-sectional surface, the sample was cleaved under ultra-high vacuum ($\sim 10^{-10}$ Torr) and transferred directly into the scanning tunneling microscope (STM) setup ($\sim 10^{-11}$ Torr) which is cooled down to 4.8 K. STM observation and STS measurements were performed on the cleaved (110) surface. No visible steps were observable by an optical microscope.

Electrochemically etched tungsten wire was used as the STM tip, which was cleaned in situ by applying pulsed high bias voltages before measurements. Topographic images were obtained in constant current mode to distinguish the superlattice structures. For STS measurements, differential conductance signal (dI/dV) as a function of the applied voltage (V) between the sample and the grounded tip was measured using a lock-in amplifier with a small modulation of V (10 mV_{pp}, 700 Hz), where I is the tunneling current. Here, STS spectra represent the normalized differential conductance [$(dI/dV)/(I/V)$] as a function of V. $(dI/dV)/(I/V)$ is known to be proportional to the LDOS, where V directly corresponds to electron energy [1].

3. Results and discussion

Figure 1 shows an STM topographic image of a cleaved surface around the interface between the InAs layer and the GaSb/InAs SL taken under constant current mode. Clear layer structures were observed without any atomic steps. The contrast depends on the electronic structure of the material. Dark regions correspond to InAs and bright regions correspond to GaSb.

STS measurements were performed along the growth direction normal to the InAs/SL interface. Figure 2(a) shows a spatial variation of the STS spectra above the Fermi-level ($V \geq 0$ V). Due to the residual impurities and the electron transfer from GaSb to InAs, the Fermi-level lies just above the InAs conduction band minimum and just below the GaSb valence band maximum. Bright regions show high LDOS and dark regions show low LDOS. GaSb energy band gaps (Zero LDOS) are indicated and are very close to the bulk value of 0.81 eV. In the SL layer, wave features in the LDOS corresponding to the confined SL subbands were observed [2]. More remarkably, clear standing waves that are not due to quantum confinement were observed in the thick InAs layer close to its interface with the SL [enhanced in Fig. 2(b)]. The oscillation wavelength becomes shorter with increasing energy. Figure 3 shows the dispersion relation extracted from the observed standing waves. For comparison, the dashed line shows the calculated dispersion including the energy band

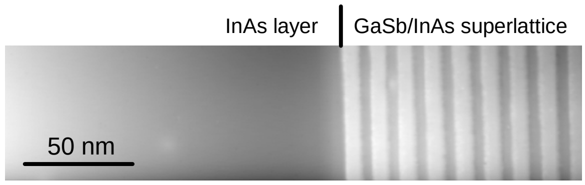

Fig. 1. STM topographic image (filled state, V = -1.0 V) of a cleaved surface around the interface between the InAs layer and the GaSb(7 nm)/InAs(6 nm) superlattice. Dark regions (InAs) and bright regions (GaSb) were clearly observed without any atomic steps.

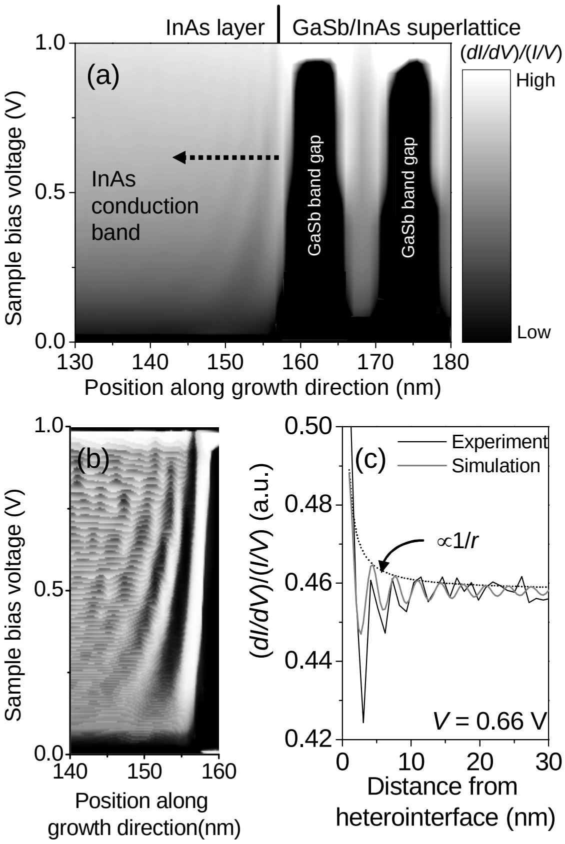

Figure 2. (a):Spatial variation of STS spectra above the Fermi level. Sample bias voltage (V) corresponds to electron energy, V = 0 V being the Fermi level. Bright regions show high local density of states (LDOS) and dark regions show low LDOS. GaSb energy band gaps (Zero LDOS) are indicated. In the InAs layer, interference patterns due to electron reflection from the GaSb barrier are seen. (b): Enhanced interference pattern. (c): The oscillation of the standing wave as a function of the distance from the heterointerface at V = 0.66 V [along arrow in (a)]. The gray solid line shows simulated oscillations bound by an envelope (dotted curve) decaying as $1/r$, where r is the distance from the heterointerface.

nonparabolicity effect where the effective mass change is taken to be $m^* = 0.023m_0(1+2\Delta E/Eg)$, where m_0 is the static electron mass, ΔE is the energy difference from the conduction band minimum, and Eg is the InAs band gap of 0.42 eV [3]. For the calculation, the conduction band minimum was taken to lie at the Fermi level. The energy difference between the experimental and calculated values becomes larger with increasing wave number. This can be attributed to the tip-induced band bending toward the cleaved surface [4]. Spatial charge distribution in the sample is modulated by the STM tip. Higher Energy (corresponding to higher V) induces larger positive tip-induced band bending.

Figure 2(c) shows the oscillation of the standing wave as a function of the distance from the heterointerface (r) at V = 0.66 V [along the arrow in Fig. 2(a)]. The gray solid line shows simulated oscillations of the from

$$\Delta\rho(r) = A\cos(kr+\delta)/r$$

(expected to be valid for $r \geq \lambda$), where $\Delta\rho$ is the relative

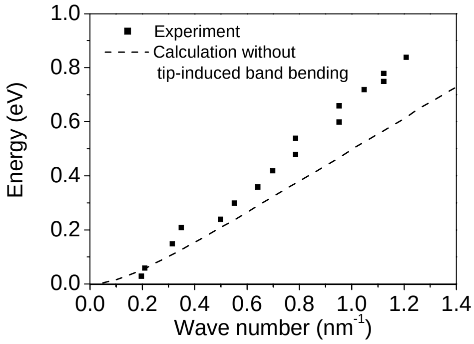

Figure 3. Dispersion relation extracted from observed standing waves. The dashed line shows the calculated dispersion including nonparabolicity effect. For the calculation, the conduction band minimum was taken to be equal to the Fermi-level and the tip-induced band bending was not included.

change in LDOS, k is the wave number, δ is the phase difference, A is a constant, and λ is the wavelength. We find that the decay in amplitude is best described by $1/r$, suggesting a three dimensional nature of the electron waves as opposed to $1/r^{1/2}$, which would indicate two-dimensional waves, as previously observed on a metal surface [5]. The phase difference shows little penetration of the electron wave into the GaSb barrier. For example, at V = 0.36 V (second subband energy in the superlattice) $\delta = 57°$ corresponds to less than 0.5 nm penetration.

We conclude that the standing waves originate from the interference between the incident and reflected electron waves at the interface. Although electron subband formation can be seen in the InAs layer of the SL, the decay and phase of the standing waves were not influenced by the subbands indicating that a 7 nm-GaSb layer is thick enough to cause complete reflection for electrons with energy in the range below the GaSb barrier height.

4. Summary

We measured spatial variation of LT-STS spectra as a function of the position normal to an InAs/GaSb heterointerface on a cross sectional surface. Clear standing waves originating from the interference between the incident and reflected electron waves at the interface were observed. A 7 nm-GaSb layer is thick enough to cause a complete electron reflection. The results demonstrate that LT-STS measurements on a cross sectional surface can be powerful for investigating electron reflection characteristics in heterostructures. Applying this technique to heterostructures with thinner layers, electron transmission characteristics can also be investigated.

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