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D-5-1 (Invited) Two-Dimensional Friedel Oscillations and Electron Confinement to Nanostructures at a Semiconductor Surface

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1. Introduction

Electron wave phenomena at surfaces has been studied recently using scanning tunneling microscopy (STM) [1]. On the noble metal surfaces, clear standing waves of electrons in the Shockley surface state bands have been observed [2, 3, 4]. In the case of semiconductor systems, standing wave patterns have been observed at cleaved (110) surfaces with a three-dimensional electron gas (3DEG) [5, 6], and at the epitaxial InAs(111)A surface, on GaAs substrate, with a two-dimensional electron gas (2DEG) at the surface accumulation layer [7, 8]. Such waves are also observed at the Si(001) surface with one-dimensional electronic states in surface state band [9], and for InAs nanostructures with zero-dimensional (0D) electronic states [7, 10].

In this paper, we present results on the oscillatory features of 2DEG local density of states (LDOS) quantized in the accumulation layer at an epitaxial InAs(111)A surface by using low-temperature STM (LT-STM). In addition to the 2DEG LDOS, we describe the LDOS characterization of 0D states in InAs nanometer-scale tetrahedrons that form at the surface.

2. Experiments

Undoped InAs layers were grown on n-GaAs(111)A substrates by molecular beam epitaxy (MBE) [11]. The sample was then transferred to the LT-STM stage in ultra-high-vacuum below 10^{-10} Torr and cooled to 5.3 K. The surface LDOS was obtained by using the dI/dV measurement with a lock-in detection technique, which was done simultaneously with the STM topography. The map of the obtained dI/dV values is known to correspond to the distribution of LDOS [4, 12].

3. Results and Discussion

Figure 1 shows an STM image and the corresponding dI/dV image. Concentric circular patterns are observed in the vicinity of the point defect (shown by an arrow). Three-fold symmetric regular peak distributions are also imaged within triangular defects. These triangular defects are the surface of stacking fault tetrahedra (SFTs) [13]. The dI/dV signal oscillations as a function of the distance from the point scatterer are Friedel oscillations of the 2DEG accumulated at the surface, this has been explained elsewhere [7, 8]. In Fig. 2, the bias voltage dependence of $k_{//}^2$ ($k_{//}$: wave number obtained from oscillation period) around a point defect and within the SFTs obtained from dI/dV signal oscillations are shown. The dependence fits well using the nonparabolic E-k dispersion relation, which is typically observed in the case of narrow bandgap semiconductors. The $k_{//}$ values, determined by LDOS peak distances in SFTs, coincide with those obtained from 2DEG Friedel oscillation around the point scatterer. This is in the case of the SFT which is relatively larger than the electron wavelength (about 20 nm). The standing waves were continuously observed at both negative and positive tunneling bias above the 2DEG subband level.

When the size of the SFT becomes comparable with the electron wavelength, the LDOS tends to be affected by the 0D quantum size effect in the SFT. In Fig. 3, the STM and dI/dV images of a SFT (side length 33.9 nm) are shown. To explain such confined states, we used a simple model that the imaged 0D LDOS can be approximated by the 2D states confined to a triangular boundary. This is because of the comparable size of SFT with the electron accumulation layer thickness (25 nm), where the electric field is vertical to the surface due to the conduction band bending. Here, the boundary is made of a positively charged hard-wall with a downward band bending near the sides of the triangular surface. Since the LDOS at the edge of the SFT mainly reveals a density peak, the dislocation there is expected to act as a donor-type defect array [14]. The measured LDOS is in good agreement with those of the calculated discrete 3rd and 4th 0D states (Fig. 3). The bias difference of 0.02 V is roughly consistent with the calculated energy separation of 0.014 eV between the two levels. We can, therefore, attribute each observed LDOS to each discrete 0D eigenstate.

4. Conclusions

The local density of states was characterized using LT-STM at the surface of the InAs thin film grown on a GaAs(111)A substrate by MBE. The dI/dV images show bias-dependent standing waves of the two-dimensional electronic states due to Friedel oscillations in the surface accumulation layer. The dI/dV images also show LDOS distribution in small tetrahedral InAs nanostructures.

Calculations reveal that the LDOS distribution in each dI/dV image in the nanostructure corresponds to a discrete 0D eigenstate.

Acknowledgments

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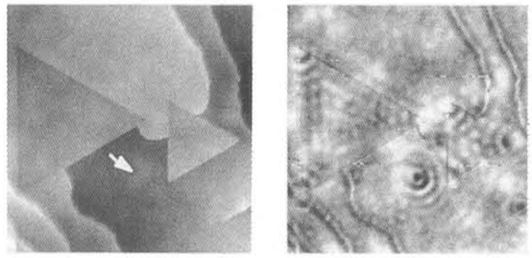

Fig.1 STM and dI/dV images at the MBE-grown InAs(111)A surface. An arrow in the STM image indicates a point defect due to threading dislocation. (5.3 K, 214 nm x 214nm, +0.1 V)

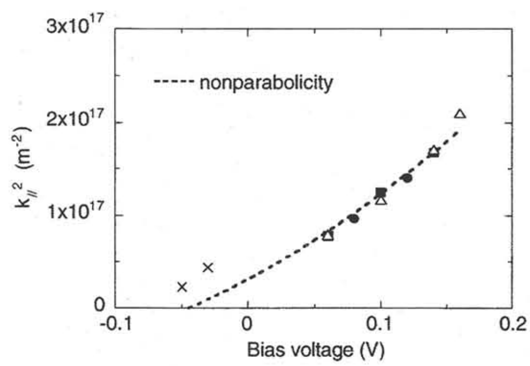

Fig.2 Bias voltage dependence of $k_{//}^2$ around a point defect (filled squares), within the SFTs (open triangles and filled circles), and at the surface by using fast Fourier transformation (FFT) spectra of the dI/dV images at negative bias (marked x).

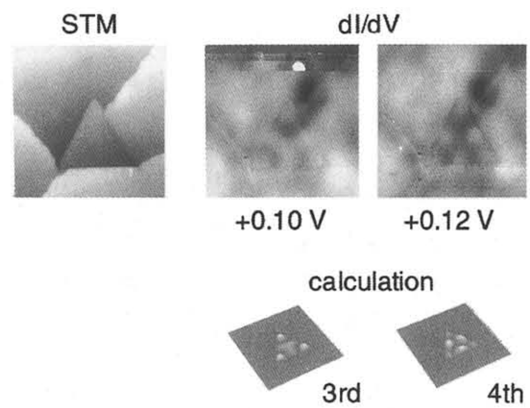

Fig.3 STM and dI/dV images of the small SFT with the side length of 33.9 nm. The dI/dV images correspond to calculated 0D states of a 3rd and 4th energy levels. (5.3 K, 67 nm x 67 nm)