STM/STS Measurements of Two-Dimensional Electronic States in Magnetic Fields at Epitaxially Grown InAs(111)A Surfaces

Y. Niimi¹, K. Kanisawa², H. Kojima¹, H. Kambara¹, Y. Hirayama²,³, S. Tarucha⁴ and Hiroshi Fukuyama¹

¹Department of Physics, University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo 113-0033, JAPAN
²NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, JAPAN
³SORST-JST, 4-1-8 Honmachi, Kawaguchi, Saitama 331-0012, JAPAN
⁴Department of Applied Physics, University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo 113-8656, JAPAN

E-mail: niimi@kelvin.phys.s.u-tokyo.ac.jp

Abstract. The local density of states (LDOS) at the epitaxially grown InAs surface on a GaAs substrate was studied at very low temperatures in magnetic fields up to 6 T by scanning tunneling microscopy and spectroscopy. We observed a series of peaks, associated with Landau quantization of the two-dimensional electron system (2DES), in the tunnel spectra just above the subband energy (−80 meV) of the 2DES. The intervals between the peaks are consistent with the estimation from the effective mass of the 2DES at the InAs surface. In a wider energy range, another type of oscillation which was independent of magnetic field was also observed. This oscillation can be explained by the energy dependence of the transmission probability of the tunneling current through the Schottky barrier formed at the interface between the InAs film and GaAs substrate.

1. Introduction
Two-dimensional (2D) electron systems (2DESs) exhibit fascinating quantum phenomena at low temperatures and in high magnetic fields. Usually, these phenomena have been studied by means of transport measurements. Recently, the 2DESs have been investigated in real space on nanometer scale using the scanning tunneling microscopy and spectroscopy (STM/STS) techniques. Morgenstern et al. [1] showed clear Landau quantization of the 2DES at a cleaved InAs (110) surface with submonolayer iron deposition as well as complicated networks of the local density of state (LDOS) depending on bias voltage with the low temperature STM/STS. More recently, distinct localized and extended states of the quantum Hall effect have been observed in the quasi 2DES of graphite [2, 3]. An InAs thin film epitaxially grown on a GaAs(111)A substrate is another candidate for investigation of the 2DESs with STM/STS. The 2DES is formed at the surface accumulation layer of InAs/GaAs(111)A, where clear Friedel oscillations of 2D LDOS were observed [4]. At this surface, the LDOS of the zero-dimensional discrete levels
was also imaged within tetrahedron structures of comparable size to the electron wavelength (∼20 nm) [5].

In this work, we studied the LDOS of the 2DES at the surface of InAs/GaAs(111)A in magnetic fields using STM/STS. Clear peak structures associated with the Landau levels (LLs) appear in the tunnel spectra at energies near the bottom of 2D subband. In the positive energy range (0 ≤ E ≤ 350 meV), a field-independent oscillation with a larger energy separation was also observed. This oscillation does not depend on the thickness of the InAs films but rather on the kinds of GaAs at the heterostructure interface. These facts suggest that the tunneling current is affected by the potential change at the interface between the InAs film and GaAs substrate.

2. Experimental
The present STM/STS measurements were performed at a base temperature of 30 mK and in magnetic fields up to 6 T using an ultra low temperature STM (ULT-STM) [6]. Mechanically sharpened Pt₀.₈Ir₀.₂ and electrochemically etched W wires were used as STM tips. 30 and 100 nm thick undoped InAs layers were grown on an n-type GaAs(111)A substrate by molecular beam epitaxy (MBE) [7], respectively. Further, a thick arsenic film was evaporated on the sample surface to prevent the surface contamination, since the sample was inevitably exposed to air when transferred from the MBE to the ULT-STM. The samples with the arsenic protection layer were loaded into an ultra high vacuum (UHV) chamber next to the ULT-STM. By heating it up to 380°C in the chamber, we can remove the arsenic layer and obtain the clean InAs surface. The sample was transferred to the ULT-STM keeping the UHV condition and cooled down to the base temperature. The differential tunnel conductance (dI/dV) signal was taken by the lock-in technique with a bias modulation V_{mod} of 1.0 mV at a frequency of 412 Hz. All the results shown here did not depend on the tip material and lock-in parameter.

3. Results and discussions
In the inset of Fig. 1(a), we show an STM image of the (2×2) reconstructed InAs(111)A surface. In spite of exposure to air, the sample surface was kept clean without any contamination, owing to the arsenic protection layer and the subsequent removal of it. A typical normalized differential conductance (i.e. (dI/dV)/(I/V)) curve in zero magnetic field is shown in Fig. 1(a). Note that the (dI/dV)/(I/V) is proportional to the sample density of states (DOS). The band gap energy of 420 meV for InAs is observed in the tunnel spectrum below the Fermi energy (E_F). A steplike structure is seen at V = −80 mV. This indicates the DOS of the 2DES in the InAs surface accumulation layer. Above E_F, a square-root structure due to the DOS of three-dimensional (3D) electron gas is superimposed on the 2D DOS (see Fig. 1(b)). These DOS structures are consistent with previous STM/STS work at the InAs/GaAs(111)A surface [4].

Figure 2 shows the (dI/dV)/(I/V) curves at several different magnetic fields (B) in a narrower energy range (−150 ≤ E ≤ 80 meV). At finite fields, several peaks (triangles) appear in the tunnel spectra. The peaks become more pronounced at higher fields, and the peak energies are roughly in proportion to B. The energy separation between two successive peaks is 24 meV at B = 6 T, which is consistent with hω_c (~ 20 meV) estimated from the effective mass (m^* = 0.03 ~ 0.04m) of the 2DES in InAs/GaAs(111)A [4]. Here h is the reduced Planck’s constant, ω_c = eB/m^* is the cyclotron frequency and m is the bare electron mass. Thus, we believe that these peaks result from the LLs of the 2DES. However, the peak amplitudes seem to be smaller than those for the adsorbate-induced 2DES at the cleaved InAs(110) surface [1]. This is presumably because the electron mobility is relatively low due to a large number of dislocations at the interface between the InAs layer and GaAs substrate. Actually, we did not clearly observe alternating localization and extension of the LDOS at the InAs/GaAs(111)A surface depending on bias voltage, such as those observed at the cleaved InAs(110) [1] and graphite surfaces [3].
In the positive energy range ($0 \leq E \leq 350\text{ meV}$), we observed another type of oscillation in the tunnel spectra (see Fig. 3(a)). The energy separation ($\sim 60\text{ meV}$) of this oscillation is larger than that of the LLs, and slightly increases with increasing energy. However, it does not depend on $B$. The phase of the oscillation slightly changes depending on sample position, but the energy separation does not. Then, we changed the InAs film thickness and/or substrate on which the InAs film is epitaxially grown. Concerning the film thickness, there is no difference between the two samples of respective film thickness 30 and 100 nm. Figs. 3(b) and (c) show the $(dI/dV)/(I/V)$ curves for an n-type InAs substrate and n-type GaAs substrate on which a 4 nm thick undoped GaAs is epitaxially grown, respectively. In the case of the InAs substrate, we did not observe such an oscillation. On the other hand, the DOS oscillation with a smaller energy separation ($\sim 30\text{ meV}$) was observed at the InAs films on the GaAs(undoped)/GaAs(n-type) substrate. From these facts, we believe that the DOS oscillation is associated with the tunneling current affected by the potential change at the interface between the film and substrate.

As the simplest model to explain the DOS oscillation, we assume the electron transmission probability $T$ through a square-well potential. $T$ is written as

$$T = \frac{4E(E - V_0)}{4E(E - V_0) + V_0^2 \sin^2(k\ell)}$$

where $k = \sqrt{2m^*(E - V_0)/\hbar^2}$, $\ell$ and $V_0$ ($\leq E$) are a width and height of the potential, respectively. $T$ has maxima ($T_{\text{max}}$) when $E = (\hbar^2/2m^*)(n\pi/\ell)^2 + V_0$. Thus, the energy

Figure 1. (a) $(dI/dV)/(I/V)$ curves in a wide energy range ($-950 \leq E \leq 500\text{ meV}$) at the InAs/GaAs(111)A surface (tunnel current $I = 0.2 \text{ nA}$, $V = 500\text{ mV}$); inset: a typical STM image of the reconstructed InAs(111)A surface ($7.5 \times 6.8\text{ nm}$). (b) Schematic illustrations of the energy band profile at the surface.

Figure 2. $(dI/dV)/(I/V)$ curves in a narrow energy range ($-150 \leq E \leq 80\text{ meV}$) in several different magnetic fields perpendicular to the sample surface ($I = 0.3 \text{ nA}$, $V = 100\text{ mV}$). Each spectrum is vertically shifted for clarity.
dependence of $T$ shows an oscillation with a period depending on $\ell$ and $n$. For example, the energy separation between $n = 1$ and 2 is 60 meV for $\ell = 25$ nm and 30 meV for $\ell = 35$ nm. In the present experiments, the square-well potential corresponds to the Schottky barrier formed at the interface between the InAs film and substrate (see Fig. 3(d)). Compared with the simple n-type GaAs substrate, a width of the Schottky barrier for the GaAs(4 nm thick undoped)/GaAs(n-type) substrate is effectively longer, hence the energy separation of the DOS oscillation is smaller. The reason why any oscillations are not observed at the InAs film on the InAs substrate is that there is no potential change at the interface between the film and substrate. Therefore, the measured DOS oscillations can be explained by the energy dependence of $T$ of the tunneling current through the Schottky barrier at the interface.

4. Conclusions
We have measured the LDOS at the InAs/GaAs(111)A surface at very low temperatures in magnetic fields up to 6 T using a ULT-STM. In finite magnetic fields, the LL peaks were observed at energies near the bottom of the 2D subband. On the other hand, above $E_F$, the field-independent oscillation with a larger energy separation appear superimposed onto the 3D DOS of the InAs/GaAs(111)A. From the STM/STS measurements for the InAs/GaAs(111)A, InAs/GaAs/GaAs(111)A and InAs/InAs(111)A, we found that this oscillation is associated with the transmission probability of the tunneling current through the Schottky barrier at the interface between the InAs film and GaAs substrate.

Acknowledgments
This work was financially supported by a Grant-in-Aid for Scientific Research from MEXT, Japan and ERATO Project of JST. Y.N. acknowledges the JSPS Research program for Young Scientists.
5. References

[1] Morgenstern M, Klijn J, Meyer C and Wiesendanger R 2003 Phys. Rev. Lett. 90 056804
[2] Matsui T, Kambara H, Niimi Y, Tagami K, Tsukada M and Fukuyama H 2005 Phys. Rev. Lett. 94 226403
[3] Niimi Y, Matsui T, Kambara H, Yoshioka D and Fukuyama H 2005 Preprint cond-mat/0511733
[4] Kanisawa K, Butcher M J, Yamaguchi H and Hirayama Y 2001 Phys. Rev. Lett. 86 3384
[5] Kanisawa K, Butcher M J, Tokura Y, Yamaguchi H and Hirayama Y 2001 Phys. Rev. Lett. 87 196804
[6] Matsui T, Kambara H and Fukuyama H 2000 J. Low Temp. Phys. 121 803; Matsui T, Kambara H, Ueda I, Shishido T, Miyatake Y and Fukuyama H 2003 Physica B 329 1653; Kambara H, Matsui T, Niimi Y and H. Fukuyama 2006 Jpn. J. Appl. Phys. 45 1909
[7] Yamaguchi H, Fahy M R and Joyce B A 1996 Appl. Phys. Lett. 69 776