Simultaneous study by scanning tunneling spectroscopy and transport measurements in adsorbate-induced two-dimensional systems

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Abstract.
An adsorbate-induced two-dimensional electron system at cleaved surfaces of InSb is investigated by low-temperature scanning tunneling microscope and spectroscopy combined with transport measurements in magnetic fields up to 10 T. The magnitude of the potential disorder obtained from the spatially averaged density of states agrees with that deduced from the analysis of the Shubnikov-de Haas oscillations.

1. Introduction
It is well-known that conduction electrons can be induced by submonolayer deposition of other materials at surfaces of narrow band-gap III-V semiconductors. Recently, the present authors have successfully performed in-plane magnetotransport measurements on adsorbate-induced two-dimensional (2D) electron systems (2DESs) at in situ cleaved surfaces of p-type InAs [1, 3, 2, 4] and InSb [5]. For an Ag-deposited InSb surface, perfect two dimensionality of the adsorbate-induced 2DES was established from the observation of the integer quantum Hall (QH) effect [5]. Moreover, results of low-temperature annealing experiments at the InSb surface suggest that surface morphology of the deposited materials strongly affects the transport properties of the induced 2DES [5]. In this paper, we report not only magnetotransport measurements but also scanning tunneling microscopy (STM) images of surface morphology of adatoms in an adsorbate-induced 2DES at InSb surfaces. In addition, we compare the magnitude of the potential disorder obtained from the spatially averaged density of states (DOS) directly with that estimated from the Shubnikov-de Haas (SdH) oscillations.

2. Experiment
The InSb samples used were cut from a Ge-doped single crystal with an acceptor concentration of $(1-2) \times 10^{21} \, \text{m}^{-3}$. In the case of p-type crystals, surface electrons are separated from three-dimensional carriers in the substrate by a depletion layer. Sample preparation is similar to that used in the previous work on InSb surfaces [5]. After sample cleaving in an ultrahigh vacuum chamber, deposition of Fe atoms was done at the surface of the cold substrate to avoid inhomogeneous distribution of adsorbates. A home-made low-temperature STM was operated with a PtIr probe tip in magnetic fields up to 10 T. Sample holder has six electrodes to measure the diagonal resistivity $\rho_{xx}$ and the Hall resistance $R_H$ of the adsorbate-induced 2DES
and to apply a sample bias voltage ($V$) for STM and spectroscopy (STM/S) measurements. Magnetotransport data on the (110) cleaved surface were taken in a Hall bar geometry ($4 \times 4 \text{ mm}^2$) using the standard four-probe lock-in technique with two current electrodes and four voltage electrodes prepared by deposition of gold films onto noncleaved surfaces at room temperature. All the data shown here were taken on optically flat InSb surfaces at 4.2 K.

3. Results and discussion

Fig. 1 shows a typical STM image of Fe atoms on the (110) cleaved surface of InSb at zero magnetic field. The Fe atoms act as donors, which bend the bands downwards and induce a 2D electron gas (2DEG) at the InSb surface. Therefore, tunneling current can flow through the induced 2DEG. Sb lattice appears as bright rows because we use a positive sample bias voltage ($V = 100 \text{ mV}$), while the Fe atoms are visible as a protrusion with a dark rim between rows of the Sb lattice. The Fe atoms are positioned slightly lower than the surface Sb atoms, which is consistent with Ref. [6]. Thirty-five Fe atoms are counted in an area of $20 \times 20 \text{ nm}^2$, which is equivalent to the Fe atomic density $N_{\text{Fe}}$ of $8.8 \times 10^{16} \text{ m}^{-2}$. At this Fe atomic density, each Fe atom is isolated and the formation of chain structures, which is expected for deposition on the substrate at room temperature, is less than five percent.

Fig. 2 shows $\rho_{xx}$ and $R_H$ at 4.2 K in magnetic fields up to 9 T at the same sample used in Fig.1. Due to low DOS of InSb 2DESs, more than one subband is occupied even at moderate total electron density [7, 8]. From the analysis of the SdH oscillations, we deduced the electron density of the first (second) subband $N_1 = 5.8 \times 10^{15} \text{ m}^{-2}$ ($N_2 = 1.7 \times 10^{15} \text{ m}^{-2}$), while the total electron density $N_e = 7.5 \times 10^{15} \text{ m}^{-2}$ was obtained from the Hall coefficient in low magnetic fields. From the ratio $N_e/N_{\text{Fe}}$, almost every 12th Fe atom donates one electron into the InSb substrate. As a result of the doping, the 2DEG is formed at the cleaved surface of InSb.

The transport mobility $\mu_t$ obtained from the zero-field conductivity $\sigma_0$ ($\mu_t = \sigma_0/eN_e$) is estimated to be 14 m$^2$/Vs, which is the highest $\mu_t$ of the adsorbate-induced 2DESs [1, 5].
quantum mobility $\mu_q$, in contrast, obtained from the damping of the SdH oscillations is found to be $1.0 \pm 0.2 \text{ m}^2/\text{Vs}$, which is similar to that of the 2DES induced by submonolayer Ag deposition at cleaved surfaces of InSb [5]. This result suggests that the charged acceptors within the inversion layer play a major role in the potential disorder.

It is well-known that the Dingle ratio is large ($\mu_t/\mu_q \gg 1$) for long-range potential fluctuations and small ($\mu_t/\mu_q \approx 1$) for short-range potential fluctuations [9]. The obtained ratio of two electron mobilities ($\mu_t/\mu_q \simeq 14$) is sufficiently larger than unity, suggesting that long-range potential fluctuations are dominant in the Fe-induced 2DES at InSb surfaces. In general, $\mu_t/\mu_q$ can be large in high-mobility modulation-doped GaAs/AlGaAs heterostructures, where the potential disorder is mainly caused by remote ionized impurities [10, 11, 12]. This discrepancy can be explained as follows. In our Fe-induced 2DES, almost every 12th Fe atom donates one electron into the InSb surface, i.e., only 8.5% of the adsorbate Fe atoms contribute to form the 2DES. Therefore, the ionization probability may be able to make the potential disorder caused by the ionized Fe atoms moderate. Additionally, the adsorbate-induced 2DES is not covered with a dielectric layer that causes interface roughness, such as a Si metal-oxide-semiconductor field-effect transistor. Hence, $\mu_t/\mu_q$ can be large in the Fe-induced 2DES at InSb surfaces.

Both the first and second subbands form the Landau level (LL) structures and contribute to the magnetoconductance. The QH effect occurs only when the Fermi level $E_F$ is in the localized states between the LLs for both subbands, in which $\rho_{xx}$ vanishes and $R_H$ is quantized as $h/ie^2$ for an integer $i$ [13, 14]. The QH effect with $i = 5$ ($i = 4$), which consists of a combination of the first subband $i_1 = 4$ ($i_1 = 3$) with the second subband $i_2 = 1$, is observed at $B = 6.2$ T ($7.9$ T). The odd-integer QH states correspond to the spin splitting.

Fig. 3 displays spatially averaged differential conductance ($dI/dV$) spectra at $B = 0$ and 10 T perpendicular to the (110) cleaved surface of InSb. We obtain the spatially averaged $dI/dV$ spectra, which coincide with the DOS of the Fe-induced 2DES, as an accumulation of typically $10 \times 10$ $dI/dV$ spectra in an area of $100 \times 100 \text{ nm}^2$. The tip-induced quantum dot states as described in Ref. [15] are not observed in our $dI/dV$ spectra. In Fig. 3(a), the spatially averaged
Figure 3. Spatially averaged $dI/dV$ spectra at $B = 0$ (a) and 10 T (b); $I = 100$ pA, $V = 100$ mV and a modulation voltage $V_{\text{mod}} = 2.0$ mV. The lowest LL (LL0) and the first excited LL (LL1) of the first subband are marked. Red and blue arrows in Fig. 3(b) represent spin direction. Dashed red and blue curves are result of a double Gaussian fitting for the LL0 at 10 T.

$dI/dV$ spectrum at $B = 0$ T shows an apparent step at $V = -50 \pm 5$ meV, representing the first subband edge $E_1$. Moreover, the second subband edge is found to be $E_2 = 2 \pm 2$ meV from the spatially averaged $dI/dV$ spectrum at $B = 14$ T (not shown). A small dip at $E_F$ ($V=0$) of Fig. 3(a) shows a Coulomb gap, which is discussed elsewhere. Based on $N_1$ and $N_2$ obtained from the analysis of the SdH oscillations, we estimated the subband edges $E_{N1}$ and $E_{N2}$ [3, 16, 17]. The values of $E_{N1} = -80$ and $E_{N2} = -29$ meV slightly differ from those of $E_1$ and $E_2$, respectively. This difference in the subband energies between $E_1(E_2)$ and $E_{N1}(E_{N2})$ is attributed to the influence of a tip-induced band bending, which is caused by a work function mismatch between the STM tip and the sample [18]. However, it is known that a small difference between the surface potentials does not significantly affect the $dI/dV$ spectra except for a slight energetic shift [19].

The spatially averaged $dI/dV$ spectrum at $B = 10$ T shown in Fig. 3(b) exhibits pronounced peak structures corresponding to spin-split LLs as a function of $V$. The effective mass $m^*$ and the Landé $g$-factor $g$ can be deduced from the separation of LLs $\hbar e B/m^*$ and of spin levels $|g|\mu_B B$ with the Bohr magneton $\mu_B$. From the lowest peak distances of the first subband at $B = 10$ T, we obtained $m^* = 0.018 m_e$ ($m_e$: free electron mass) and $|g| = 36$. These values slightly differ from those of InSb at the conduction band minimum $m^* = 0.0135 m_e$ and $|g| = 51$ [20] due to the well-known nonparabolicity of the conduction band of InSb [21].

The potential disorder can be obtained not only from the SdH oscillations but also from the $dI/dV$ spectra. The full width at half maximum of the lowest LL in the spatially averaged $dI/dV$ spectrum at $B = 10$ T is $\Delta V_{\text{DOS}} \approx 22.3$ mV, analyzed by a double Gaussian fit with a single width parameter $\Delta V_{\text{DOS}}$ [22, 23]. In contrast, the average width of the single pot $dI/dV$ is $\Delta V_s = 20.7 \pm 1.2$ mV at $B = 10$ T. We evaluate the width of the potential disorder to be $\Delta_{\text{dis}} = \sqrt{\Delta V_{\text{DOS}}^2 - \Delta V_s^2} \approx 8.4$ meV, which is in the same way in Ref. [23]. On the other hand, from $\mu_1$ obtained from the damping of the SdH oscillations, the level broadening of the LLs is found to be $\hbar/\tau_q = \hbar e/m^* \mu_q \approx 8.6$ meV, where $\tau_q$ is the single-particle scattering time.
magnitude of the potential disorder obtained from the spatially averaged $dI/dV$ spectra is in good agreement with that estimated from the damping of the SdH oscillations in the Fe-induced 2DES at InSb surfaces.

4. Summary
An Fe-induced 2DES at cleaved surfaces of InSb is investigated by low-temperature STM/S combined with transport measurements in magnetic fields up to 10 T. The magnitude of the potential disorder obtained from the spatially averaged DOS is estimated to be approximately 8.4 meV, which is comparable to that deduced from the damping of the SdH oscillations. Our STM/S combined with magnetotransport measurements will be applied to further studies on magnetism [2] and superconductivity [24] in one-atomic-layer metal films.

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