Low-temperature scanning tunneling spectroscopy study of two-dimensional electron systems confined in semiconductor heterostructures

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Abstract. Low-temperature scanning tunneling spectroscopy under ultra-high vacuum was employed to investigate the two-dimensional electron system at the epitaxial surface of Si-doped In0.53Ga0.47As/In0.52Al0.48As(111)A quantum-well structures. The electron density in the near-surface region of the quantum well could be controlled through modulation doping. Spectra of the electronic local density of states in the conduction band showed a clear step-like energy dependence that reveals the subband states. In spectra acquired at some areas of nanometer size, peaks were observed near subband minima, indicating the existence of bound states.

1. Introduction
Two-dimensional electron systems (2DES) not only play a crucial role in modern electronic devices like field-effect transistors [1], but also offer the opportunity to investigate experimentally many fascinating phenomena, including quantum confinement [2], resonant impurity states [3], integer quantum Hall effect [4], fractional quantum Hall effect [5], Anderson localization [6], and metal-insulator transitions [7,8]. Scanning tunneling spectroscopy (STS) would allow to probe the electronic local density of states (LDOS) of 2DES at the nanometer scale. STS measurements of 2DES reported so far have been conducted mainly on metal surface states [9,10], metal thin films [11,12], and the electron accumulation layer at InAs surfaces [13-15]. However, it would be preferable to study 2DES confined in epitaxially grown semiconductor quantum-well (QW) structures, because of their technological importance, the possibility to directly compare STS measurements with electrical transport measurements, and the ability to precisely control the main parameters (such as the QW thickness, the potential barrier height, the impurity concentration and distribution, and the electron density). In a very recent work [16], the cleaved surface of InAs/GaSb QW structures was investigated by STS, and clear LDOS standing waves corresponding to confined subband states were imaged in the
heterostructure cross-sectional plane. Yet another interesting possibility is to focus on epitaxial surfaces of QW structures, to measure the spatial distribution of LDOS in the 2DES plane. In this proceeding, we report a low-temperature STS study of the 2DES at the epitaxial surface of In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As(111)A QW structures.

**Fig. 1.** STS study under UHV of (111)A-oriented In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As QW structures. L denotes the QW thickness.

### 2. Experimental details

Experiments were carried out in a multi-chamber ultra-high vacuum (UHV) system, which includes a low-temperature scanning tunneling microscope (STM) chamber and a molecular beam epitaxy (MBE) chamber. Si-doped In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As thin film structures were grown by MBE on lattice-matched InP(111)A substrates, at a growth rate of 0.1 ML/s and a substrate temperature of 450°C. After the growth, samples were rapidly taken out from the MBE chamber, transferred under UHV to the low-temperature STM, and cooled down to 5 K.

Fig. 1 shows the schematic sample structure. STS was measured on the clean, as-grown surface of the In_{0.53}Ga_{0.47}As QW, where electrons form a 2DES confined between vacuum and a 5-nm-thick In_{0.52}Al_{0.48}As barrier. Two different QW thicknesses (L = 10 nm and L = 15 nm) were investigated in this work. The QW was uniformly doped by Si around 1 \times 10^{16} cm^{-3}. The barrier was doped around 4 \times 10^{18} cm^{-3}, except in a 2.5-nm-thick undoped spacer used for some samples.

A small modulation (10 mV peak-to-peak, 700 Hz) was added to the sample voltage \( V \) (tip neutral), and the differential conductance \( dI/dV \) was recorded through a lock-in amplifier. \( dI/dV \) spectra were normalized by the conductance \( I/V \), to cancel the exponential dependence of the transmission coefficient on \( V \) and tip-sample separation [17]. \( (dI/dV)/(I/V) \) as a function of \( V \) is, in general, a good representation of the LDOS as a function of energy [17,18].

There are three main reasons for using (111)A-oriented In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As QW structures for STS measurements. Firstly, both In_{0.53}Ga_{0.47}As and In_{0.52}Al_{0.48}As can be grown by MBE on lattice-matched InP substrates, leading to high-quality thin films without any misfit dislocations [19]. Secondly, the large conduction-band (CB) offset between In_{0.53}Ga_{0.47}As and In_{0.52}Al_{0.48}As [20,21] makes this heterojunction system attractive for fabrication of QW structures. Thirdly, it is expected that electrons released in the QW layer by Si donors are not captured by acceptor surface states, because the density of acceptor surface states is negligible in the band gap at the In_{0.53}Ga_{0.47}As(111)A clean surface [22], as described later. In other words, the (111)A-oriented In_{0.53}Ga_{0.47}As QW is not depleted, in contrast with what should happen for a GaAs or a (001)-oriented In_{0.53}Ga_{0.47}As QW. In the experiments described here, this conductive In_{0.53}Ga_{0.47}As QW layer was in direct electrical contact with the STM stage, through indium deposited on the edges of the InP substrate before the growth. Therefore, the sample voltage \( V \) was directly applied between the QW layer and the grounded STM tip. Since the voltage drop in the conductive QW layer is negligible, \( V \) corresponds to the energy of the states in the QW. In such a configuration, voltage drop in the barrier is avoided.

### 3. Results and discussions

Figs. 2(a)-(c) show typical LDOS spectra by STS at the surface of In_{0.53}Ga_{0.47}As QWs. Each spectrum corresponds to a spatial average over a 25 nm \( \times \) 25 nm surface area. The measured band gap is about...
0.8 eV, which is comparable with the value reported by photoluminescence measurement at 7 K [23].

The LDOS in the CB has a step-like energy dependence, as expected for a 2DES. The subband spacing decreases with increasing \( L \). Four [Figs. 2(a) and 2(b)] and five [Fig. 2(c)] subbands are observed for \( L = 10 \) nm and \( L = 15 \) nm, respectively. The quantized energy level positions were calculated using a simple one-dimensional model [Fig. 2(d)]. The only adjustable parameter in the simulation was the CB offset between In\(_{0.53}\)Ga\(_{0.47}\)As and In\(_{0.52}\)Al\(_{0.48}\)As, \( \Delta E_C \). Good agreement between calculation and STS data was obtained for \( \Delta E_C = 0.55 \) eV, which is consistent with previously reported values of 0.50 (± 0.05) eV [20] and 0.55 (± 0.02) eV [21].

The spectra of Fig. 2 indicate that the surface Fermi level (FL) is located in the 1\(^{st} \) subband (electric quantum limit). It means that most of the electrons released by bulk Si donors are not trapped by acceptor surface states. This is because at the In\(_{0.53}\)Ga\(_{0.47}\)As(111)A clean surface the density of acceptor surface states in the band gap is negligible [22]. In addition, the surface FL position depends on the undoped spacer thickness. The surface FL is located around the middle of the 1\(^{st} \) subband if no spacer is present in the barrier [Fig. 2(a)], while it is at the bottom of the 1\(^{st} \) subband for a spacer thickness of 2.5 nm [Fig. 2(b)]. Thus, the electron density in the near-surface region of the QW, which is probed by STS, can be readily controlled through modulation doping in the barrier. This is a confirmation that the density of acceptor surface states in the CB is small [22].

Fig. 2. STS measurements at 5 K of In\(_{0.53}\)Ga\(_{0.47}\)As surface QWs. LDOS spectra for (a) \( L = 10 \) nm (without undoped spacer), (b) \( L = 10 \) nm (with a 2.5-nm-thick undoped spacer in the In\(_{0.52}\)Al\(_{0.48}\)As barrier), and (c) \( L = 15 \) nm (with a 2.5-nm-thick undoped spacer). The FL position (\( V = 0 \) V) is indicated by an arrow. Hatched regions correspond to the band gap. (d) Simple one-dimensional model for the calculation of quantized energy levels in the QW [24]. The electron effective mass at the bottom of the CB in the In\(_{0.53}\)Ga\(_{0.47}\)As QW and the In\(_{0.52}\)Al\(_{0.48}\)As barrier is \( m_{c1} = 0.041 \) \( m_0 \) and \( m_{c2} = 0.075 \) \( m_0 \), respectively. For In\(_{0.53}\)Ga\(_{0.47}\)As, the non-parabolicity of the CB is taken into account. The In\(_{0.53}\)Ga\(_{0.47}\)As electron affinity is \( \chi = 4.485 \) eV. The CB offset between In\(_{0.53}\)Ga\(_{0.47}\)As and In\(_{0.52}\)Al\(_{0.48}\)As, \( \Delta E_C \), is the only adjustable parameter. Vertical lines in spectra (a)-(c) show the calculated energy level positions for \( \Delta E_C = 0.55 \) eV.
Fig. 3. Spatially-resolved STS measurements at 5 K of an In$_{0.53}$Ga$_{0.47}$As surface QW ($L = 15$ nm, with a 2.5-nm-thick undoped spacer in the In$_{0.52}$Al$_{0.48}$As barrier). (a) STM topography. (b) Corresponding LDOS spatial map at $V = +0.06$ V (near the 1$^{st}$ subband minimum). Bright regions correspond to high LDOS. The cross indicates the center of a nanometer-size area where LDOS is the highest. (c) LDOS spectra as a function of the distance $r$ from the cross. Dashed vertical lines show the positions of the peaks which appear near subband minima. (d) Height of the peak at $V = +0.06$ V (near the 1$^{st}$ subband minimum), as a function of $r$. The peak height is divided by the value taken by $(dI/dV)/(I/V)$ at $V = 0.06$ V and $r = 14$ nm. Also shown: exponential decay $1 + A \exp(-2r/a)$, where $a$ is the effective Bohr radius for a shallow donor state splitting off from the 1$^{st}$ subband in a 15-nm-thick In$_{0.53}$Ga$_{0.47}$As QW, calculated using a variational model [27]. Two extreme cases are considered: donor impurity located at the center ($a = 14$ nm) and at the boundary ($a = 22$ nm) of the QW. The value of $A$ is chosen to obtain the best fit of the experimental data, and is different for the two cases.

It should be noted that the position of the surface FL with respect to the subband minima was found to vary as a function of position, indicating potential fluctuations in the QW. One possible origin for such inhomogeneities may be the random potential created by ionized Si donors in the barrier [25]. The spectra of Fig. 2 are taken from area of maximum electron density.

In the spectra shown in Fig. 2, the normalized differential conductance $[(dI/dV)/(I/V)]$ as a function of $V$ has a negative slope in high-order subbands (the slope in the 1$^{st}$ subband, which is crossed by the FL, is slightly positive). According to our calculations using tunneling theory [17,18], the negative slope does not correspond to a real LDOS feature, but is simply an artifact due to normalization. However, the position of the quantized energy levels is not affected by the normalization.

Fig. 3 shows spatially-resolved STS measurements at the surface of an In$_{0.53}$Ga$_{0.47}$As QW ($L = 15$ nm). One monolayer step is visible in the STM topograph [Fig. 3(a)]. LDOS spatial maps at energies near subband minima reveal a nanometer-size area where LDOS is higher [Fig. 3(b)]. In LDOS spectra acquired on such a singular spot there is a peak near each subband minimum [Fig. 3(c)]. This is the typical signature of the localization of subband states by an attractive potential. According to the theory of 2DES, any localized attractive potential results in the formation of a bound state splitting off from the bottom of the continuum [26]. In the case of a multi-subband 2DES, as studied here, a bound state appears for each subband, resulting in a ladder of bound states. This is exactly what observed in Fig. 3(c). In our case, the attractive potential may be related to an ionized Si donor, i.e. the localized states of Fig. 3 may correspond to shallow impurity states in the QW structure. Such a phenomenon has been studied experimentally by resonant Raman scattering [3], but has never been investigated before by spatially-resolved measurements such as STS. From here, let us assume that the localized states of Fig. 3 are actually Si donor states. The spatial extension of the state splitting off from the 1$^{st}$ subband can be estimated by plotting the peak height as a function of position [Fig. 3(d)]. Theory predicts that the effective Bohr radius of a donor state in a QW structure depends on the position of the
donor impurity along the growth direction. As a first approximation, a variational model for a symmetric QW with infinitely high barriers \[27\] can be used. In the case of a 15-nm-thick In\(_{0.53}\)Ga\(_{0.47}\)As QW, calculations give a Bohr radius \(a = 14\) nm and \(a = 22\) nm for an impurity located at the center and at the boundary of the QW, respectively. Fig. 3(d) shows that the Si donor states of Fig. 3 correspond to a Si atom closer to the center of the QW than to the boundaries.

4. Conclusion

In summary, low-temperature STS under UHV was employed to investigate the 2DES at the epitaxial surface of Si-doped In\(_{0.53}\)Ga\(_{0.47}\)As/In\(_{0.52}\)Al\(_{0.48}\)As(111)A QW structures. The electron density in the near-surface region could be controlled through modulation doping. Both extended subband states and localized states were observed in LDOS spectra. Thus, it was demonstrated that the (111)A-oriented In\(_{0.53}\)Ga\(_{0.47}\)As/In\(_{0.52}\)Al\(_{0.48}\)As heterojunction system is well suited for STS studies of epitaxial surfaces of semiconductor QW structures.

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