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Imaging and probing electronic properties of self-assembled InAs quantum dots by atomic force microscopy with conductive tip

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Atomic force microscopy with a conductive probe has been used to study both the topography and the electronic properties of 10-nm-scale self-assembled InAs quantum dots (QDs) grown by molecular beam epitaxy on *n*-type GaAs. The current flowing through the conductive probe normal to the sample surface is measured for imaging local conductance, while the deflection of cantilever is optically detected for disclosing geometrical structure. The conductance on InAs QDs is found to be much larger than that on the wetting layer, allowing imaging of QDs through measurements of local current. We attribute this change in conductance to the local modification of surface band bending associated with surface states on InAs QD surface. Mechanisms of electron transport through QDs are discussed based on current–voltage characteristics measured on QDs of various sizes. © *1999 American Institute of Physics.* [S0003-6951(99)03206-4]

Self-assembled quantum dots (QDs) grown on lattice-mismatched substrates have been widely studied because of their potential importance for device applications and of their significance in the study of low dimensional electron systems.[1] In particular, electronic properties of InAs QDs grown on (001) GaAs have been extensively studied on an ensemble of QDs by techniques such as photoluminescence (PL), absorption spectroscopy, and capacitance spectroscopy.[2–7] Recently, however, various attempts have been made to disclose properties of individual QDs by local probes.[8,9] Atomic force microscopy (AFM) has been one of the most successful and provided us with abundant morphological information about InAs QDs, but rarely with their electronic properties.[10–12]

In this letter, we report on AFM study with a conductive probe in which simultaneous imaging of topography and conductance of InAs QDs is achieved together with local current versus bias voltage ($I-V$) bias characteristics.[13] Here, the conductive AFM probe ''touches'' a nm-scale spot of the sample surface, and a bias voltage can be applied directly onto a nanostructure which lies between the surface and the substrate in contrast to scanning tunneling microscopy in which much of the voltage is supported across the vacuum gap. Hence, the conductive AFM probe allows us to modify the local band profile and enables us to investigate the electron transport through the nanostructures. We show that a much larger current flows when the conductive AFM tip is on a QD than on the wetting layer since the surface states on InAs QDs lower the local Schottky barrier well below that on the wetting layer. We also show how local $I-V$ characteristics depend on the QD size, and discuss the transport mechanisms.

InAs QDs used in this study were grown by molecular beam epitaxy (MBE) on n^+-(001) GaAs substrates with a donor concentration of $2\times10^{18}\,\mathrm{cm}^{-3}$. The substrate was thermally cleaned under an As_4 flux of about 7×10^{-6} Torr beam equivalent pressure, followed by growth of a 0.5-μm-thick Si-doped ($2.5\times10^{18}\,\mathrm{cm}^{-3}$) GaAs layer at a substrate temperature of about 570 °C. Then the substrate temperature was lowered to 450 °C at which nominally 2.3 monolayers of InAs (average thickness of 0.7 nm) were deposited without substrate rotation to form QDs of various concentrations and sizes. After removal from the MBE system, the sample was detached from the molybdenum block under a flow of dry nitrogen to minimize oxidation. It was then brought into a commercial high-vacuum AFM system (SPA300HV, Seiko Instruments Inc.) where measurements were performed under a pressure of less than 5×10^{-7} Torr at room temperature. InAs QDs were probed in a contact mode while a sample bias voltage (Vs) was applied to the substrate with respect to the tip. The deflection of the cantilever and the current flowing through the tip were measured simultaneously in order to image the topography and the conductance. The AFM probe was made of semi-insulating silicon and coated with a thin gold or cobalt film in order to warrant conductivity. During scanning, the probe was in contact with the sample surface with constant repulsive force which was in the range of 10–40 nN. The obtained data were independent of the kind of the metal and the applied force in this range. Although the radii of the conductive tips are not ex-

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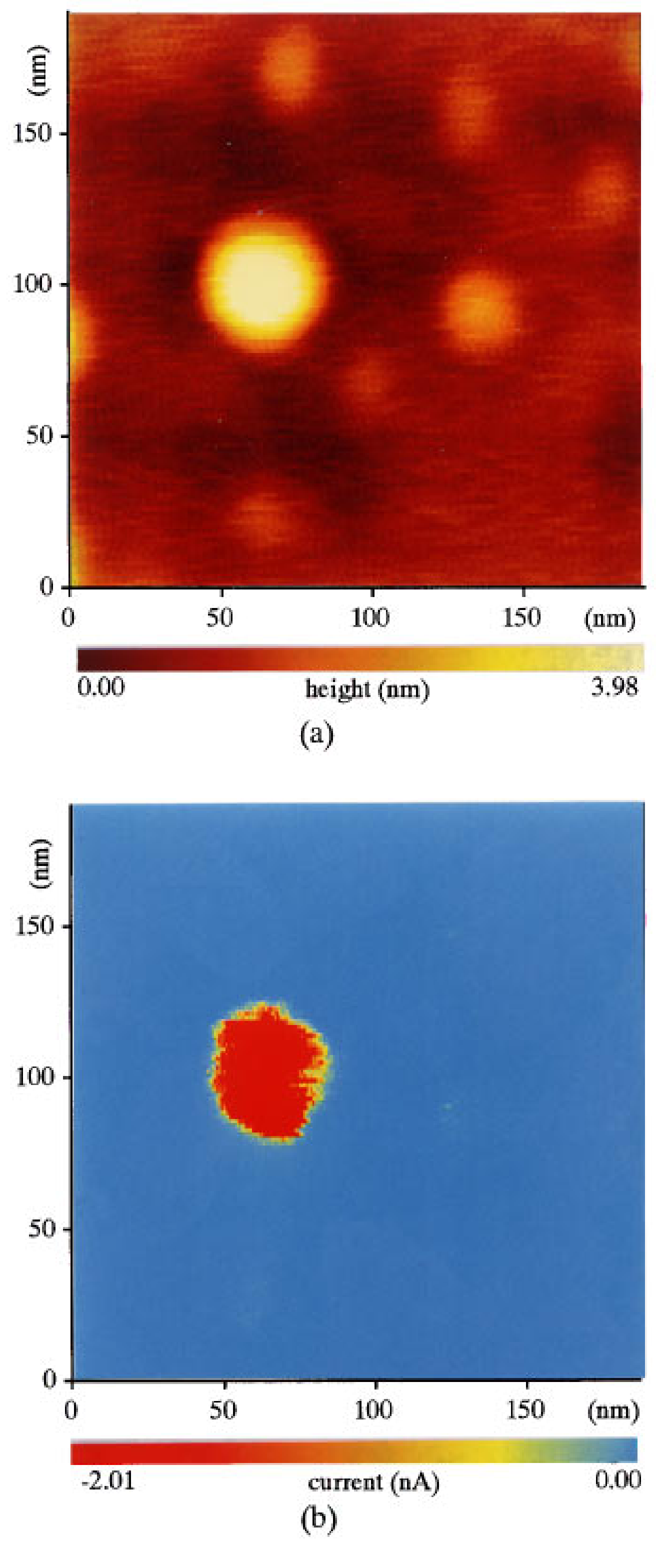

FIG. 1. (a) The topographic image and (b) the current image of self-assembled InAs QDs grown on GaAs (001) surface simultaneously obtained at a sample bias voltage of −50 mV.

actly known, they were sharp enough that the diameter of our regular QDs were observed to be about 20 nm agreeing with previous reports.[10]

Topographic and conductive (or current) images of InAs QDs obtained simultaneously at Vs of −50 mV are shown in Figs. 1(a) and 1(b), respectively. A large QD of 50 nm in diameter and several small QDs of about 20 nm in diameter are clearly observed in the topography, whereas only the 50 nm QD is seen in the current image. Conductance images of the smaller QDs were collected by applying Vs of −0.6 V as shown in Fig. 2 since the conductance on the wetting layer remains low even at this voltage. These results indicate that smaller QDs are less conductive than larger QDs.

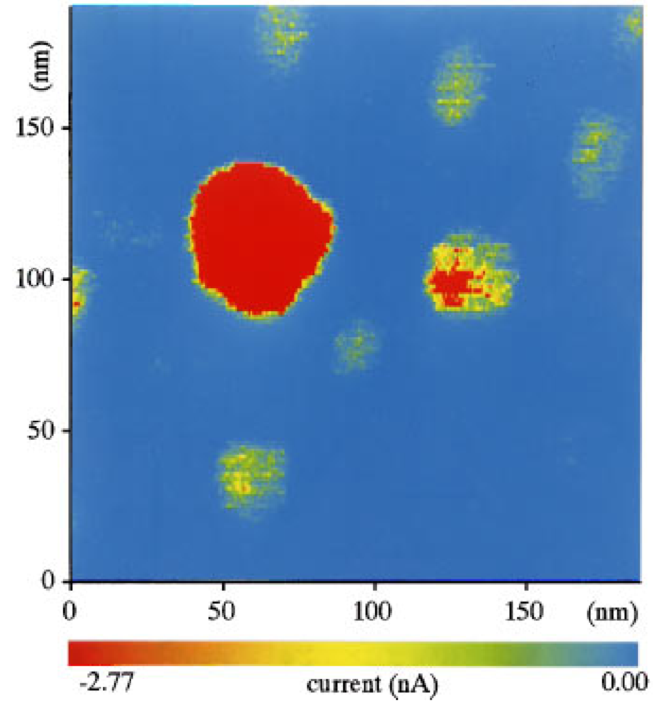

FIG. 2. The current image of InAs QDs taken with a sample bias voltage of −0.6 V.

To clarify the transport mechanisms, $I-V$ characteristics were measured on InAs QDs of various sizes and the wetting layer, as shown in Figs. 3(a)–3(d). Here, a negative Vs corresponds to a forward bias condition. When the tip is on the wetting layer, the resistance is typically over 10 GΩ and the current remained below our detection limit (10 pA) for $-0.8\,\mathrm{V} < Vs < 0.5\,\mathrm{V}$. In contrast, as shown in Fig. 3(d), an ohm-like $I-V$ was obtained on a large QD of about 100 nm in diameter with a resistance as low as 80 kΩ. Smaller QDs, on the other hand, exhibited characteristics similar to those of Schottky junctions as shown in Figs. 3(b) and 3(c). These results show that the sample-to-tip conductance is locally enhanced by InAs QDs with higher conductance on larger QDs.

The wetting layer, which is a monolayer of InAs, is likely to be oxidized in air together with a few layers of GaAs underneath. Hence, the wetting layer region of the sample is likely to show properties similar to that of the oxidized GaAs surface. In fact, we obtained similar $I-V$ characteristics from measurements on bulk n-GaAs, i.e., without InAs, where no current was observed under small bias voltages and an abrupt current increase occurred at large bias voltages. On the oxidized GaAs surface, the Fermi level is pinned at midgap by surface states, resulting in formation of a surface depletion layer. When a small conductive tip is in contact with such a depletion layer, the region just below the tip would form an extremely small nanoscale Schottky diode, which we name tip-contact Schottky diode.

When a forward bias of about 0.7 V is applied to an electrode of normal μm-scale Schottky diode, the depletion layer below the μm-scale metal electrodes disappears, resulting in the onset of current. In the case of our tip-contact Schottky diode, however, this band lowering by bias voltage is strongly blocked or buffered by the negative surface states in the region just outside the tip-contact Schottky diode. In other words, the Fermi level pinning is so strong that the surface potential just outside the contact-electrode remains to be pinned at around midgap even at this bias voltage, and the potential beneath the contact electrode does not follow the applied bias voltage. This bias voltage cancellation by surface states is most prominent in the circumference of the Schottky contact and, therefore, prevents the current from flowing most effectively in the tip-contact Schottky diode.

We now discuss the transport through QDs. It is well known that high density ($10^{12}\ \mathrm{cm}^{-2}$) positively charged surface states exist on the surface of InAs.[14] We therefore expect similar positive surface states to exist on the InAs QDs. Because of the band offset between GaAs and InAs, a depletion layer barrier, which we call heterojunction barrier hereafter, is formed on the n-GaAs side of n-GaAs/InAs QD interface. This heterojunction barrier is qualitatively similar to the Schottky barrier, and electrons in the n-GaAs layer first pass through the heterojunction barrier, and flow into an InAs QD, then reach the conductive tip which is positively biased with respect to the sample. Once electrons flow into a QD, they will smoothly drain out to the tip, as metals are known to form ohmic contacts with InAs. Hence, the resistance from the sample to the tip is determined mainly by the heterojunction barrier. In this diode structure, the QD acts as an electrode of 20–100 nm diameter since InAs makes a highly conductive contact with the tip. Here, the bias voltage cancellation by the negative surface states of the surrounding wetting layer and the height of the heterojunction barrier are taken into account to explain the $I-V$ characteristics. Compared to the Schottky barrier in the tip-contact diode, it is easier to lower the heterojunction barrier beneath the QD by a forward bias voltage because the cancellation is less effective for larger electrodes. Hence, the QDs are more conductive than the wetting layer. Though the height of the heterojunction barrier is not exactly known, we expect it to be lower for larger QDs because of more positive charges on their surfaces. In addition, the bias voltage cancellation is again less effective for larger QDs. It was reported that electron transport through a metal-semiconductor Schottky barrier with nanoscale inhomogeneity depends on the comparison of the inhomogeneity size with the depletion width.[15,16] The QDs at the heterojunction barrier are inhomogeneous, and if the depletion width is comparable with the radius of the small QDs, the surrounding heterojunction barrier prevents electron transport through the small QDs.

With 100 nm QDs, dislocations which might exist at the heterointerface can form leakage current paths which can also explain the $I-V$ curve in Fig. 3(d). However, it is widely accepted that regular QDs are free from interface dislocations, and hence we believe that linear leakage current is not dominant in Figs. 3(b) and 3(c), although further investigation is warranted.

In summary, we have successfully obtained current images of self-assembled InAs QDs grown on GaAs by AFM with a conductive probe. The conductance on QDs is found to be larger than that on the wetting layer, which is attributed to the band lowering effect by surface states on the InAs QD.

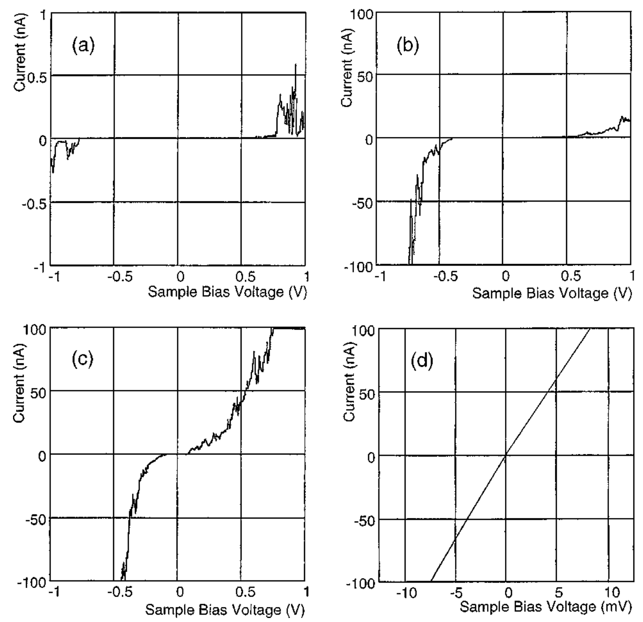

FIG. 3. $I-V$ characteristics of current flowing between the conductive tip and (a) the wetting layer, (b) a 20 nm QD, (c) a 50 nm QD, and (d) a 100 nm QD.

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