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Coulomb blockade and negative differential resistance at room temperature: Self-assembled quantum dots on Si (110) surface

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ABSTRACT

Self-assembled quasi periodic Quantum Dots (QDs) were grown by depositing two monolayers of Ir (iridium) on Si (silicon) (110) surface. We investigated the physical and chemical properties of these QDs with the help of Scanning Tunneling Microscopy/Spectroscopy (STM/STS) and X-ray Photoelectron Spectroscopy (XPS). STM images showed that the surface was covered with large terraces corrugated with quasi periodic superstructure of QDs. I(V) (current (voltage)) curves measured on the QDs showed that conductance around Fermi level is highly suppressed. In addition to that the I(V) curves measured on the QDs has a plateau at approximately 1.5 V above the Fermi level indicating negative differential resistance (NDR). XPS data suggests that the terraces are made out of Ir and at the interface between Ir terraces and Si(110) surface, Ir-silicide forms. The shifts in position of Ir 4f and Si 2p peaks associated with Ir-silicide formation were comparable with the previously known bulk Ir-silicides.

Introduction

We recently showed that Ir-silicide nanowires would grow on Si (110) surface after depositing a quarter of a monolayer of Ir and annealing the sample at 800 °C. The nanowires grow along [001] direction and have a band gap of about 0.5 eV [1]. However, when the amount of Ir coverage on the surface is increased to two monolayers, large, relatively flat terraces start to grow. A closer look at these terraces reveals that these terraces are not atomically flat but corrugated with quasi-periodic, metallic Quantum Dots (QDs). It has been known that by controlling the deposition and annealing temperatures, small islands of different sizes and symmetries can form on closely packed surfaces of noble metals [2]. For example, during epitaxial growth on Ag (111) surface at room temperature, Ag atoms form islands that are one-atom thick [2,3]. Another example is the growth of the second layer of Na atoms on Cu(111) surface where growth occurs via island formation [4–6]. The final morphology of the surface depends strongly on the interaction of adatoms with the substrate as well as parameters of the growth process such as evaporation rates, temperature, pressure, and etc [7–10]. By designing surfaces with a certain strain-relief pattern, it is possible to form ordered arrays of equally spaced monodispersed quantum dots by atom diffusion and deposition [11]. Therefore, observed quasi-periodic lattice of Ir-QDs suggests that on this surface there must be a strain-relief process creating nucleation sites for the QDs. The stress on the islands is due to the lattice mismatch between Ir and Ir-silicide crystals. A detailed study of the interface, possibly using cross-sectional TEM, can be useful to understand atomic structure of the interface and estimate the direction and magnitude of the stress built on the terraces.

In general, QDs can be metallic or semiconductor. In a semiconductor QD, electrons are confined in all three dimensions down to a length scale in the order of Fermi wavelength, therefore the energy spectrum of a QD becomes discrete. Because of that, the semiconductor QDs may also be called artificial atoms. In metallic QDs, the electrons have relatively high density, large effective mass and short phase coherence length which magnifies the importance of the charging energy associated with Single Electron Tunneling (SET) to/from the QDs while downplaying the quantized energy spectrum. In a large metal island, charging effects due to the transfer of a single electron across a junction is negligible and usually associated with shot noise [12]. However, for sufficiently small islands, charging starts to play a significant role in the tunneling spectrum [13–18]. An activation energy is required to overcome the electrostatic force between electron tunneling to/from the island and the charge of the island [19]. Due to this activation energy, it is not possible to pass current when the bias across the tunnel junction is lower than certain threshold value. In analogy with the opening of a band gap of a semiconductor, this reduction in the conductivity around zero bias is called Coulomb blockade. To observe Coulomb blockade, the total capacitance of the QDs should be smaller than $e^2/2kT$ and the resistances of the tunnel junctions should be larger than the resistance

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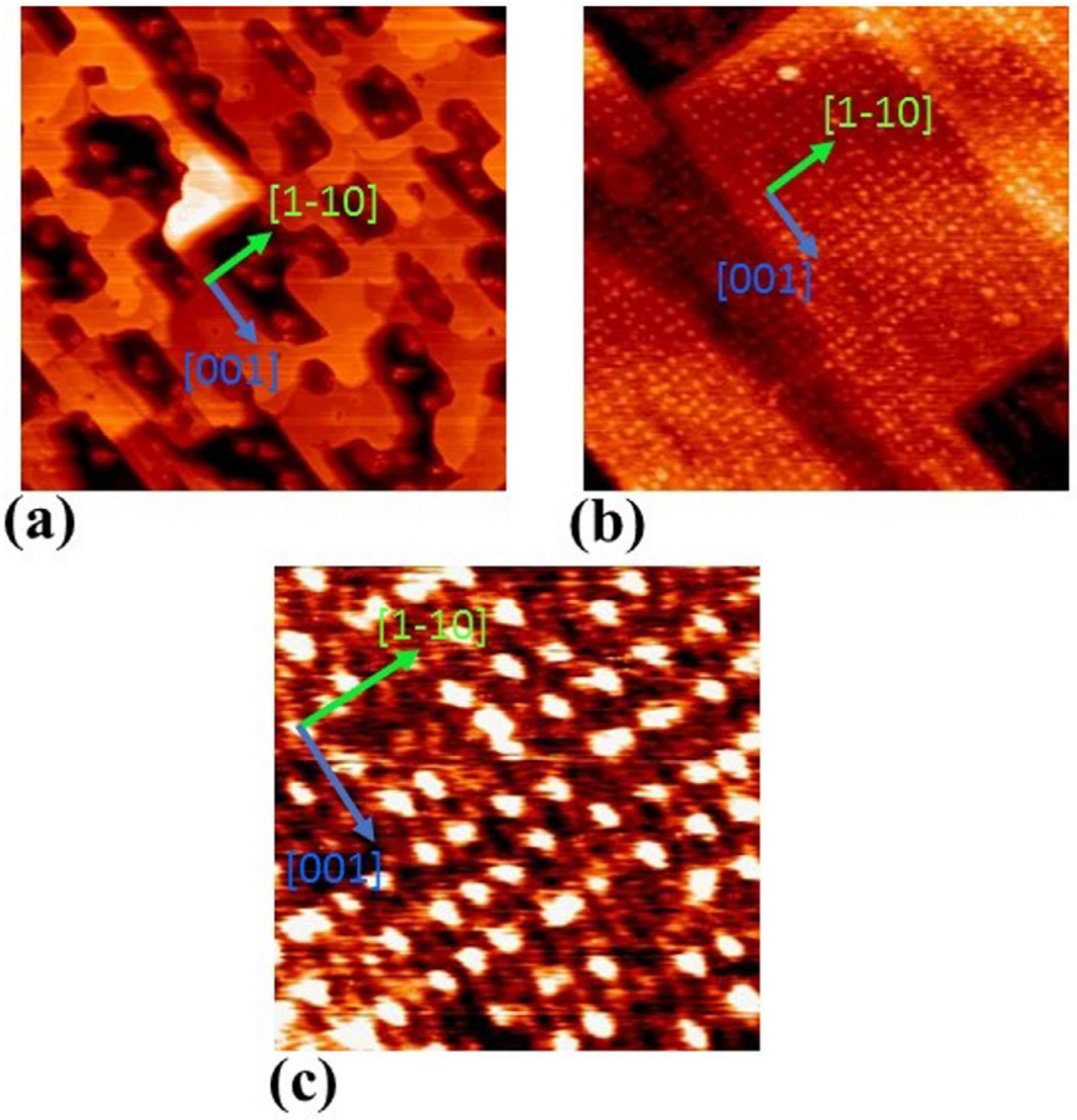

Fig. 1. (a) is 0.52 μm × 0.52 μm STM image, tunneling voltage/current are −1.48 V and 0.47 nA, (b) 57 nm × 57 nm STM image, tunneling voltage/current are −1.97 V and 0.30 nA and (c) 13 nm × 13 nm STM image, tunneling voltage/current are −1.93 V and 0.24 nA. The green and blue arrows indicate high-symmetry directions of the underlying Si(110) surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

quantum $h/2e^2$ [20].

In this paper, we report Scanning Tunneling Microscopy/Spectroscopy (STM/STS) data to reveal structure and electronic properties of Ir-QDs which exhibit both Coulomb blockade and negative differential resistance at room temperature. We also present X-ray Photoelectron Spectroscopy (XPS) data to discuss chemical composition of the surface.

2. Experiments

The Si(110) samples used in this paper were cut from nominally flat 50.8 mm × 0.5 mm, double side-polished n-type (phosphorous doped, R = 0.05–0.5 Ohm-cm) wafers. The samples were mounted on Mo holders and contact of the samples to any other metal during preparation and experiment was carefully avoided. The STM/STS studies have been performed by using an ultra-high vacuum system (UHV) with a base pressure of 2×10^{-10} *mbar*. The XPS experiments were conducted in a PHI-5400 XPS system with a base pressure of 2×10^{-10} *mbar*. The XPS system also has Ar^+ sputter gun. Before introducing Si(110) samples into the UHV chamber, samples were washed with isopropanol and dried under the flow of nitrogen gas. Si (110) samples were degassed extensively and after that flash-annealed at 1250 °C. Sample temperature was measured with a pyrometer. The quality of the clean Si(110) samples was confirmed with STM prior to Ir deposition. Ir was deposited over the clean Si(110) surface from a current heated Ir wire (99.9%). All the STM experiments were performed at room temperature. I(V) curves were measured at every point of the image while measuring an STM images of the surface. Then the measured I(V) curves were averaged. The dI/dV curves were calculated from the measured I(V) curves [21]. Once the samples were prepared in the STM chamber, they were quickly transferred to the XPS chamber with 2×10^{-10} mbar base pressure. The samples were sputtered for 8 min with 1 KeV Ar^+ ions. The samples were measured by an Al Kα (1486.6 eV) X-ray source with a pass energy of 89.5 eV (1 eV/step) and 8.95 eV (0.025 eV/step) for survey and high-resolution scans, respectively. We analyzed all the XPS core-level spectra with least-squares minimization curve fitting program. Si (Ir) core-level peak was fitted using a symmetric (asymmetric) Gaussian instrument response function convolved with Lorentzian core-level line shape (GL). For both Ir 4f and Si 2p peaks, the secondary electron background was subtracted using a