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Electronic Charged States of Single Si Quantum Dots with Ge Core as Detected by AFM/Kelvin Probe Technique

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1. Introduction

Electron charging and discharging characteristics of nanometer-size Si dots are primarily of concern in the development of single electron transistors [1] and quantum dot floating gate MOS memories [2]. Recently, we have demonstrated that an AFM/Kelvin probe technique [3] enables us to characterize the electronic charged states of nanometer Si dots covered with ultrathin SiO_2 on Si(100) through the surface potential changes caused by electron injection and emission. In the cases that the dots are far away from each other with respect to the lateral resolution in the Kelvin probe mode, the charged states of a single Si dot with 1~2 electron or holes have been measured distinctly [4]. To control the electron storage in the dots and enhance the carrier confinement, the introduction of Ge core into Si dots [5] is thought to be a significant way.

In this work, to reveal a role of the Ge core in charge storage, we have extended our research to the investigation of the charged states of a single Si dot with Ge core.

2. Experimental

Si dots with Ge core have been prepared on 4nm-thick SiO_2 thermally-grown on p-Si(100) with the following procedure. Hemispherical single-crystalline Si dots with an areal density of ~$4x10^8$ cm^{-2} were first grown by controlling the early stages of low-pressure chemical vapor deposition (LPCVD) using SiH_4 [6]. Subsequently, Ge deposition was performed on pregrown Si dots/SiO_2 at 400°C using 5% GeH_4 diluted with He and then followed by Si cap deposition under a SiH_4 pressure of 0.02Torr at 540°C. High-resolution TEM, XPS and AFM measurements were carried out to confirm the formation of Si dots with Ge core. Electron and hole injection to each Si dot with or without Ge core was performed by scanning an electrically-biased AFM probe with a tapping mode. The probe biases with respect to the Si(100) substrate were -3V for electron injection and +1 to +3V for electron emission. Before and after electron charging or discharging, the topographic and corresponding surface potential images were simultaneously measured with non-contact Kelvin-probe mode.

3. Results and Discussion

AFM images taken after each deposition steps confirm the selective deposition of Ge on pregrown Si dot and subsequent selective Si cap formation (Fig.1(a)-(c)). The evolution of the dot height with progressive deposition steps is clearly seen in Fig. 1(d). The formation of spherical nanometer dots made of the Si clad and an ellipsoidal Ge core as confirmed form cross-sectional TEM images (Fig. 1(e)), in contrast to the hemispherical pure-Si dots pregrown on SiO_2. This result implies that the structural strain energy generated at the Si/Ge interface is larger than that of the bonding energy at Si/SiO_2 interface.

Topographic and the corresponding surface potential images of a single Si dot with Ge core, whose height is ~16nm, measured with the Kelvin probe mode are shown in Fig. 2. Before the voltage application to the sample surface, a uniform surface potential is detected (Fig. 2(b)). After electron injection to the dot by applying -3V in the tapping mode, the potential image taken in the Kelvin probe mode shows the surface potential change of ~120mV on the dot (Fig.2 (c)), but no surface potential change elsewhere. Obviously, the stored electron can be extracted by applying the tip bias of +1V to the charged dot on tapping mode (Fig. 2(d)). It is interesting to note that, the surface potential change near the peripheral region of the

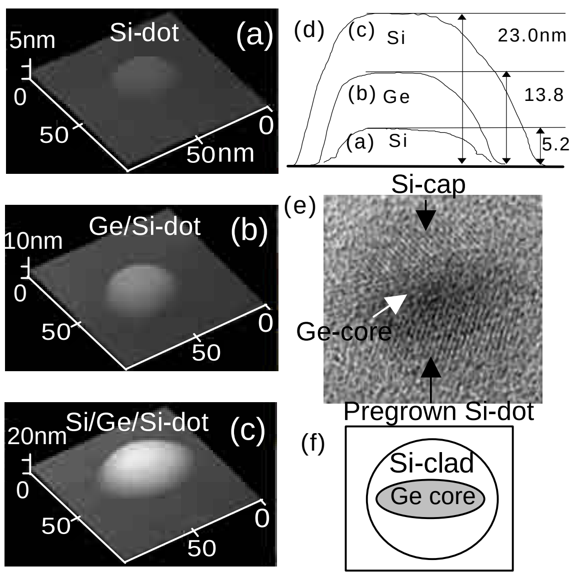

Fig. 1. Typical AFM images of the pregrown Si-dot (a) subsequent Ge deposition on the Si-dot (b) and after Si-cap formation (c), The height profiles for the cases of (a)-(c) measured in a bisector of the dot are shown in (d). (e) and (f) are cross sectional HR-TEM image of an isolated dot after Si-cap formation and its schematic view, respectively.

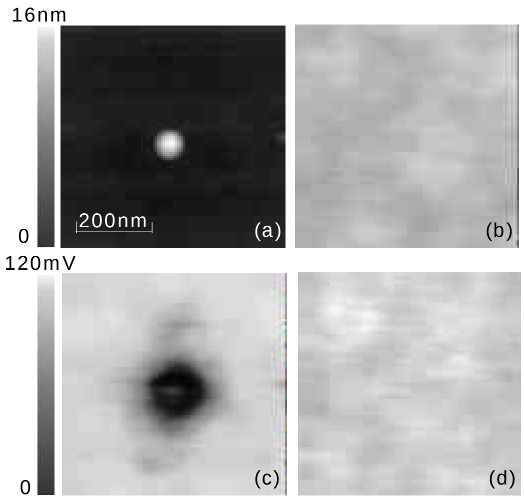

Fig. 2. Topographic image (a) and corresponding surface potential images of an isolated Si dot with a Ge core measured by AFM/Kelvin probe mode before (b) and after injected (c) at –3V, and after electron emission at +1V from the charged SI dot in the tapping mode (d). The total dot height was ~16nm

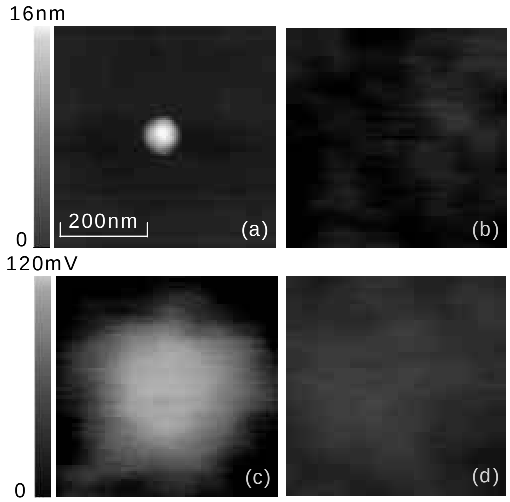

Fig. 4. Topographic image (a) and corresponding surface potential images of an isolated Si dot with a Ge core with a total dot height of ~16nm measured by AFM/Kelvin probe mode before (b) and after injected (c) at +3V, and after electron emission at -1V from the charged Si dot in the tapping mode (d).

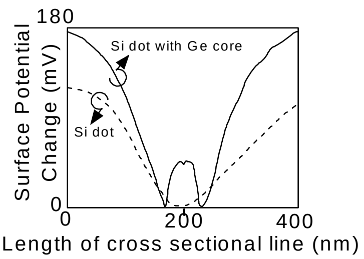

Fig. 3. Surface potential profiles of the isolated Si dots with (solid line) without (dashed line) Ge core after electron injection. The dot height is ~8nm for the pure Si dot and 16nm for the Si dot with Ge core.

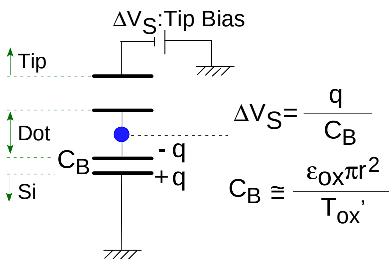

Fig. 5. Equivalent circuit of AFM/Kelvin probe measurement, where ΔVs is tip bias, q and C_B are the electronic charge in dot and capacitance between the dot and the substrate, respectively. T_{ox}' is equivalent oxide thickness, ε_{ox} is SiO_2 dielectric constant and r is dot height.

charged dot with Ge core is much higher than that of the center of the dot after electron injection as indicated in Fig. 3, in contrast to the pure Si dot case in which the potential change becomes its maximum in the central part of the dot. The result implies that the injected electron is located in the Si clad rather than the Ge core. The electron extraction from the neutral dot and the neutralization of the positively charged dot are also verified from the surface potential change of ~84mV by applying +3 and –1V to the dot in the tapping mode as indicated in Fig. 4. Notice that, for the electron extraction from the neutral dot, the maximum potential change appears in the center of the dot as observed in the charge injection to Si dot without Ge core, suggesting the hole retention in the Ge core. Observed difference in the surface potential profile between the charged states for electron and hole can be interpreted in term of a type II band discontinuity expected in the energy band diagram for a nanometer Si/Ge heterostructure.

Using an equivalent circuit model for Kelvin probe measurements (Fig. 5), we found that the potential changes observed in Fig. 2 (c) and 4 (c) are equal to the theoretically predicted values for charging the dot by 3 electrons and ~2 holes, respectively.

4. Conclusion

We have successfully detected the charging state of a single Si dot with Ge core by the surface potential change with electron charging to the neutral dot, discharging of the charged dot and electron extraction from the neutral dots by a AFM/Kelvin probe technique.

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