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Impact of phosphorus doping to multiple-stacked Si quantum dots on electron emission properties

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A B S T R A C T

We have fabricated multiple-stacked phosphorous doped Si quantum dots (P-doped Si-QDs) embedded in SiO_2 on n-Si(100) structures and characterized their field electron emission under DC bias application to semitransparent Au top-electrodes. At applied biases of −8 V and over, the electron emission signal with a peak kinetic energy at ~2.0 eV was detected. In addition, we also found that the electron emission was drastically enhanced with an increase in the applied DC bias over −11 V. The applied bias dependence of emission intensities shows that the P-doped Si-QDs is effective to improve electron emission efficiency while undoped Si-QDs stack is suited to low power operation. This indicates that electric field was reduced near the top side of the Si-QDs stack and an increase in electron injection rate from the n-Si(100) to the dots by phosphorus doping plays a role on high efficient electron emission from the Si-QDs stacked structures.

1. Introduction

Nanometer-size Si structures have been attracting considerable interest because their unique physical properties associated with quantum size effects lead us to development of novel Si functional devices such as multiple-valued memory [1,2], light emitting diodes [3–5] and electron emission devices [6–8]. In particular, as for the electron emitting device application, high density formation and size uniformity of Si nanostructures are major technological concerns when it comes to improving power efficiency and dimensional stability. Previously, we have demonstrated the formation of multiple stacked Si quantum dots (QDs) embedded in a SiO_2 matrix by repeating a process sequence consisting of dot formation by controlling the early stages of low pressure chemical vapor deposition (LPCVD) using a SiH_4 gas, surface oxidation and subsequent surface modification by remote plasmas [9]. Recently, we have also reported that electron emission from the multiple stacked Si-QDs structure covered with Au-top electrodes under DC bias application at −6 V was detected by using a non-contact atomic force microscopy technique with a conductive cantilever [10]. From a view point of the electron emission efficiency, phosphorus doped (*p*-doped) Si-QDs is one of a promising candidate because of improvement of electron injection rate into the stacked Si-QDs structures due to conduction electrons and ionized P donors [11]. In this work, we extended our research work to form multiple staked P-doped Si-QDs embedded in SiO_2 matrix and characterized the kinetic energy and intensity of emitted electron in comparison to multiple stacked undoped Si-QDs structures.

2. Experimental

After conventional wet-chemical cleaning steps, ~3.5-nm-thick SiO_2 was grown on n-Si(100) by dry O_2 oxidation at 1000 °C. The SiO_2 surface was exposed to remote Ar plasma and then to remote H_2 plasma for termination with OH bonds, where a 60-MHz power source was used to generate the remote plasmas. Subsequently, Si-QDs whose areal dot density, average dot height and full width at half maximum of dot height distribution were $\sim 5\times10^{11}$ cm^{-2}, 5 nm and 2.4 nm, respectively, were formed from the thermal decomposition of pure SiH_4 under 66.6 Pa at 560 °C and followed by radical oxidation of 1% O_2 diluted with He under 13.3 Pa at 560 °C to cover the dot surface conformally with ~2.0 nm-thick SiO_2. In phosphorus doping to Si-QDs, 1% PH_3 diluted with He was injected in a short pulse during the Si-QDs formation. From XPS measurement, the phosphorous concentration in QDs was roughly estimated to be 0.2% [12]. In addition, we also confirmed the activation of phosphorous by measuring the threshold voltage for electron emission from Si-QDs, where the electron extraction was performed with an electrically biased AFM tip and the surface potential change of the Si-QDs was measured by Kelvin force microscopy (KFM) as a function AFM tip voltage [13]. By repeating a process sequence consisting of the formation of Si-QDs and the surface oxidation and subsequent surface modification by remote plasmas, 6-fold stack structures of P-doped Si-QDs embedded in the SiO_2 network were formed. Because each QD was formed randomly on OH-terminated SiO_2 layers covering the Si substrates and Si-QDs, the QDs were

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not vertically aligned. Finally, semitransparent Au (~10 nm in thickness) and Al were formed as top and back side electrodes, respectively, by thermal evaporation.

Surface morphologies were measured by using atomic force microscopy (AFM) in a contact mode. In addition, current images were also taken by AFM in a non-contact mode with a distance between a tip and sample of ~200 nm by means of an Au-coated Si cantilever at room temperature in atmosphere. For the current image measurements, negative biases were applied to the Al back contact with respect to the grounded Au top electrode. Energy distribution of the emitted electrons was also evaluated by an electron energy analyzer in an x-ray photoelectron spectroscopy (XPS) system using electrostatic and magnetic lenses at room temperature under an ultrahigh vacuum condition.

3. Results and discussion

A topographic image of the 6-fold stack P-doped Si-QDs shows bumpy surface with a dot density of ~10^{11} cm^{-2} and an average size of ~30 nm in diameter, as shown in Fig. 1(a). We confirmed the separation of each Si dot by surface potential measurement using KFM before and after electron injection to the Si-QDs by scanning sample surface with an AFM cantilever which was electrically biased as described in Ref. [14]. We also confirmed no significant changes in the surface morphologies with and without the Au film deposition. This result indicates that the 6-fold stack P-doped Si-QDs structures were uniformly covered with the Au film. When the topographic images were taken at the tip-sample distance of ~200 nm under the DC bias application to the Au-top electrode in the range from 0 to −10 V, homogeneous images were obtained. This result denotes that there was no detectable electrostatic interaction between the sample surface and tip. In current images, uniform contrast was confirmed at applied biases of −4 V and below. In contrast to this, inhomogeneous contrasts were detected in the current images at applied biases of −5 V and over, as shown in Fig. 1(b) and (c). This result indicates that the electron emission occurred from the multiple stacked Si-QDs structures. It should be noted that an areal density of current spot is higher than that of Si dot as confirmed from Fig. 1(a) and (c). This result may be attributed to electron emission from the second or third topmost Si-QDs reflecting the misalignment of the Si-QDs stack in addition to that from the topmost Si-QDs. It should be noted that the emission current level at a specific point evaluated from the current images was increased exponentially with an increase in the applied bias over −5 V as shown in Fig. 2. To get a better understanding of electron emission process from the 6-fold stack P-doped Si-QDs structure, the kinetic energy distribution of emitted electrons were evaluated by using the hemispherical analyzer in an XPS system. In this measurement setup, the accelerating bias was applied between the Au top electrode and the hemispherical analyzer for improving detection efficiency of emitted electrons. Obviously, electron emission in the kinetic energy range from 0 to 4.2 eV from the 6-fold stack P-doped Si-QDs structures was detected where sample and accelerating biases were −13 V and 10 V, respectively, as shown in Fig. 3. We also confirmed that emission

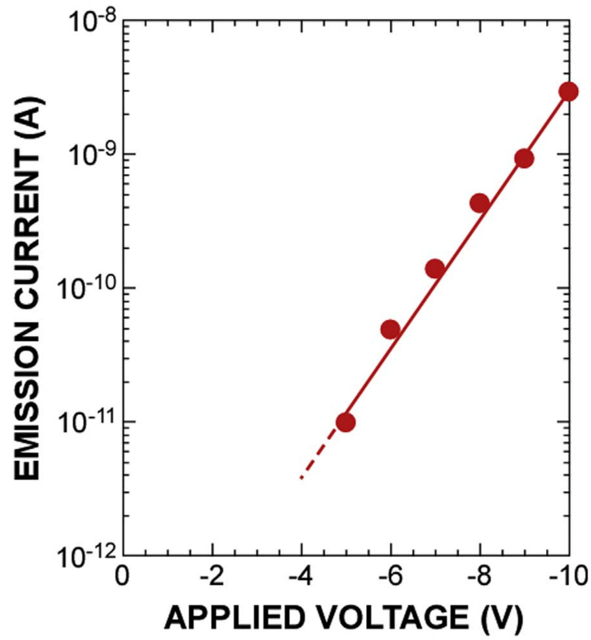

Fig. 2. Applied bias dependence of electron emission current from 6-fold stack of P-doped Si-QDs structure evaluated from current images.

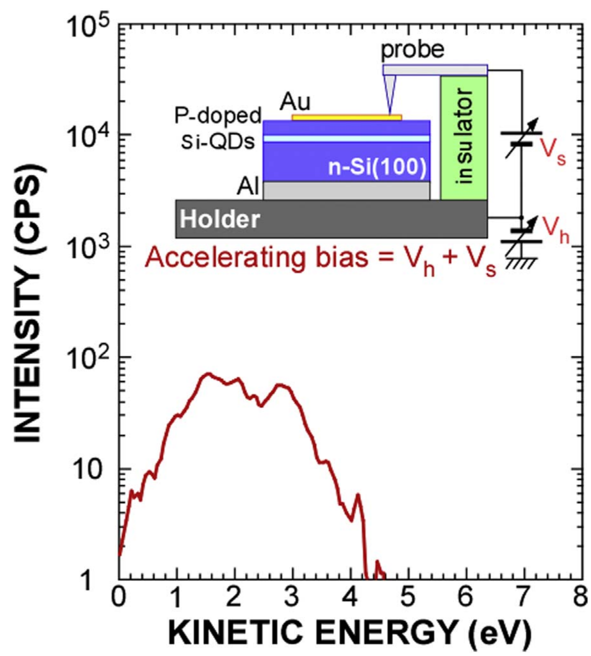

Fig. 3. Kinetic energy distribution of emitted electrons for the 6-fold stack P-doped Si-QDs structure at an applied bias (Vs) of −13V where accelerating bias was applied at 10 V. Experimental measurement set up is also shown in the inset.

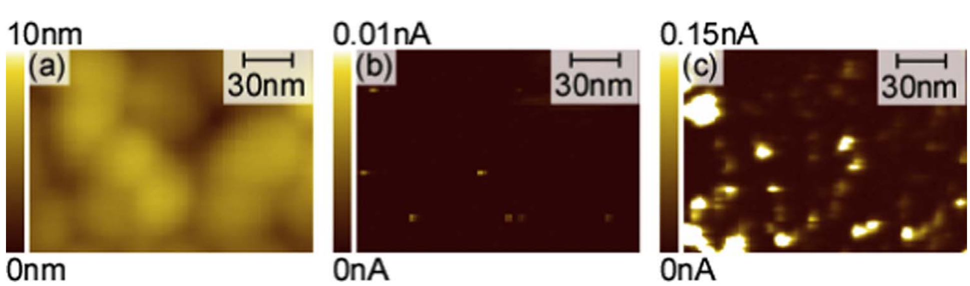

Fig. 1. A topographic image (a) and electron emission current images at sample voltages of −5 V (b) and −10 V (c) for a 6-fold stack structure of P-doped Si-QDs measured by using atomic force microscopy system.