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Structures and Field Emission Characteristics of Ion Irradiated Silicon Nanowire Arrays

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Silicon nanowire (SiNW) arrays irradiated by energetic Si ions were fabricated by metal vapor vacuum arc (MEVVA) ion implantation method. Hetero-structure of amorphous/crystalline nanowire was formed in which structure of the implanted region on the top of the nanowires was amorphous while the structure of unimplanted region on the bottom remained crystal. Field emission (FE) properties of the SiNW arrays could be improved and modulated by different implantation doses. A low turn-on field of 4.63 V/μm was observed in the SiNWs irradiated by 21 keV Si ion with a dose of 7.86×10^{16}/cm^2, and the applied field for the emission current density reaching 100 μA/cm^2 is only 5.52 V/μm. The main reason for the efficient emission is attributed to the formation of amorphous SiNWs and structure defects after implantation. The ion irradiated SiNWs after post-annealing at high temperature had better FE property due to eliminating the restrain effect to electrons.

Keywords: Silicon Nanowires, Ion Irradiation, Field Emission.

1. INTRODUCTION

Silicon is a kind of semiconductor material which plays an important role in the microelectronic and integrated industry, and SiNWs have been focused on due to their promising properties and applications in field emission characterization.[1,2] Great interest has been brought to fabricate SiNWs,[3–11] among which chemical etching method is a simple and effective way to synthesize orientated SiNWs. Moreover, a great amount of research has been done for modification of SiNWs in order to getting better properties, including doping,[12,13] bombardment of metal onto nanowires[14] and post-annealing,[15] etc. Ion implantation into silicon materials, especially to thin film materials,[16,17] has been a long practice to modify the field emission properties by controlling various dopants with different doses. However, there is a little study on ion implantation to the well aligned SiNW arrays and their FE properties.

In present work, the fabrication of SiNWs with chemical etching process and post-processing with ion implantation has been investigated. Additionally, the field emission properties of the as-grown SiNWs and ion irradiated SiNWs with different ion doses have been determined and discussion.

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2. EXPERIMENTAL DETAILS

The as-grown SiNWs were fabricated in a relatively simple chemical etching method originated from the approach Peng provided.[9,10] After the cleaning procedures, the N(100) silicon wafers were immersed into solution to be etched into SiNWs. Impurity removal was performed by boiling the samples in concentrated HNO_3 for 30 min and immersing them in the HF solution to etch away the silver catalyst and the oxide layer, respectively. Subsequently, Si ion irradiation was carried out by the means of MEVVA system at mean energy of 21 keV to dose ranging from 1.57×10^{16} to 7.86×10^{17}/cm^2. Thermal annealing was performed at 850 °C and 1100 °C for 2 h in hydrogen respectively.

The morphologies of all the obtained SiNWs were analyzed by using the scanning electron microscope (SEM S-4800, Hitachi), and the high-resolution transmission electron microscope (FEI TECNAI F30, PHILIPS) was employed to characterize the structure of SiNWs. The field emission property measurements of the obtained SiNWs were carried out in a setup composed mainly of an ultra-high vacuum chamber with the pressure of 1×10^{-7} Pa at room temperature. The anode and the cathode are a stainless steel disk and a copper disk with sample adhered parallel to, respectively. The distance of the two poles could be adjusted by a manipulator and indicated by an electronic digital display indicator. High voltage impressed

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on the samples was detected by a digital multimeter (MASTECH).

3. RESULTS AND DISCUSSION

Figure 1 shows the SEM images of Si ion irradiated SiNWs with doses of 1.57×10^{16}, 7.86×10^{16}, 1.57×10^{17} and $7.86 \times 10^{17}/\text{cm}^2$, respectively. Morphology change could be indicated in the images that the microstructures of SiNWs were heavily damaged after higher ion irradiated dose. With the low irradiated dose, the top morphology, such as the tiny tips on the top, could be maintained. While with the increase of the irradiation dose, the top of SiNWs was hit and changed to smooth morphology. Especially irradiated at the heaviest dose (seen Fig. 1(d)), there were not only without any aculeate tips to be observed on the SiNWs surface, but also to be connected to form network structure.

The microstructure of the SiNWs implanted with a high dose of $7.86 \times 10^{17}/\text{cm}^2$ was studied by HRTEM and SAED, and shown in Figure 2. Figure 2(a) shows the HRTEM image of the irradiated region on the top of a nanowire where there is an irregular atom distribution to be obtained after ion irradiation. The dispersive diffraction circles in the inset of Figure 2(a) shows the formation of amorphous Si. While in Figure 2(b), it can be seen that SiNW at the bottom remains well single crystal with regular orientation and diffraction spots of single crystal Si. After ion irradiation, heterostructure was formed in which structure in the top was amorphous with plenty of defects and in the bottom was crystal.

In order to understand the influence of structure transformation on the electron emission, the field electron emission of the ion irradiated SiNWs was carried out in a bi-pole measurement system. Figure 3(a) illustrates the curves of electron emission current density versus electric field from the as-grown SiNWs and SiNWs irradiated with different doses. Figure 3(b) displays the corresponding Fowler–Nordheim (F–N) plots, the obtained straight lines from which indicate that the emission is indeed caused by a vacuum tunneling effect. The comparison between the FE properties of as-grown and ion irradiated ones reveals that the ion-irradiation process significantly reduce the turn-on field and the applied field of electron emission. For instance, the applied fields reaching the emission current of 200 $\mu\text{A/cm}^2$ reduces from 6.25 V/μm for as-grown SiNWs to 5.91, 5.86, 6.05 and 6.14 V/μm for the irradiated dose of 1.57×10^{16}, 7.86×10^{16}, 1.57×10^{17} and $7.86 \times 10^{17}/\text{cm}^2$, respectively.

There are electron stopping loss of energy and nuclear stopping loss of energy during ions implanted into substrates. Electron stopping effect makes more target atoms to be excited because ion energy is transferred to electrons

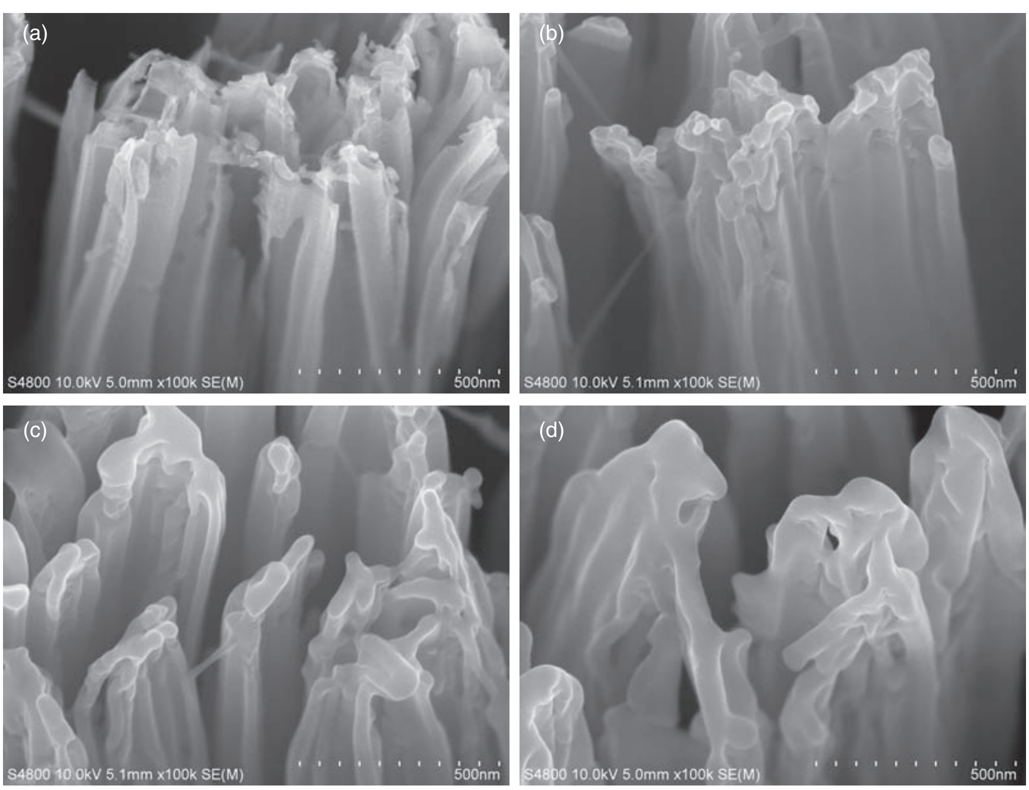

Fig. 1. SEM images of the SiNWs irradiated with different Si ion doses. (a) $1.57 \times 10^{16}/\text{cm}^2$; (b) $7.86 \times 10^{16}/\text{cm}^2$; (c) $1.57 \times 1017/\text{cm}^2$; (d) $7.86 \times 10^{17}/\text{cm}^2$.

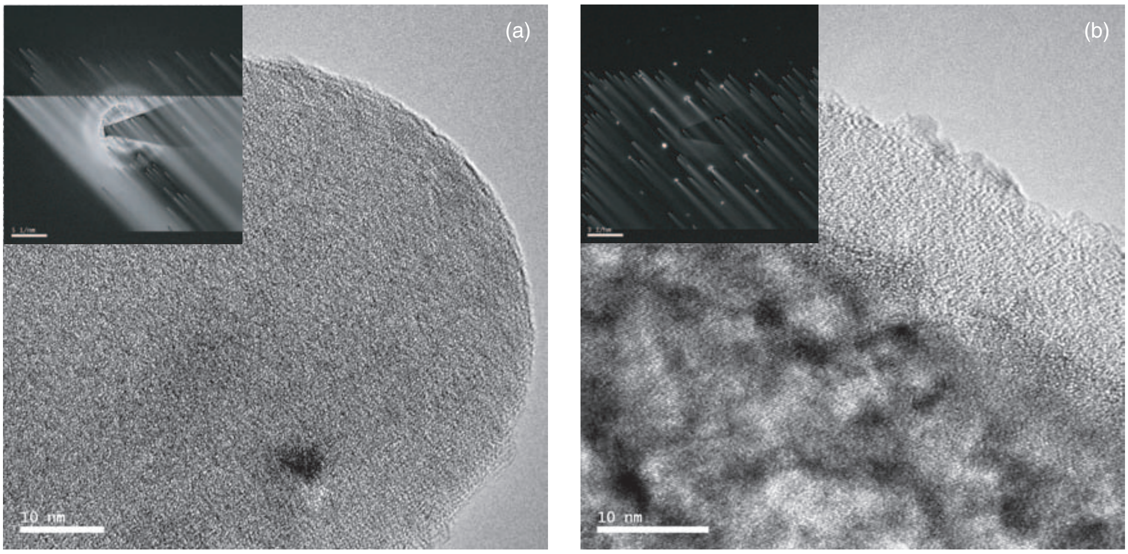

Fig. 2. TEM images of the SiNWs with Si ion implanted dose of $7.86 \times 10^{17}/cm^2$; (a) top; (b) bottom; the insets are SAED images of (a) and (b) respectively.

out of target atomic nucleus during colliding between ions and target atoms. The transferred energy is less for the ion irradiation with lower energy. While for the nuclear stopping effect, the ions transfer most of their energy to the target atoms during lower energy ion irradiation and a plenty of the displacement atoms and vacancies are formed. The stopping effects of SiNWs implanted with energetic Si ions are calculated by the TRIM program and show in Figure 3(c). It can be seen that nuclear stopping effect is much more crucial than electron stopping effect for Si ion irradiation with the energy of 21 keV. Those indicate that the defects effect is significant to the FE improvement. Electrons could be emitted directly from defect band to vacuum band or they could shift easily to the surface

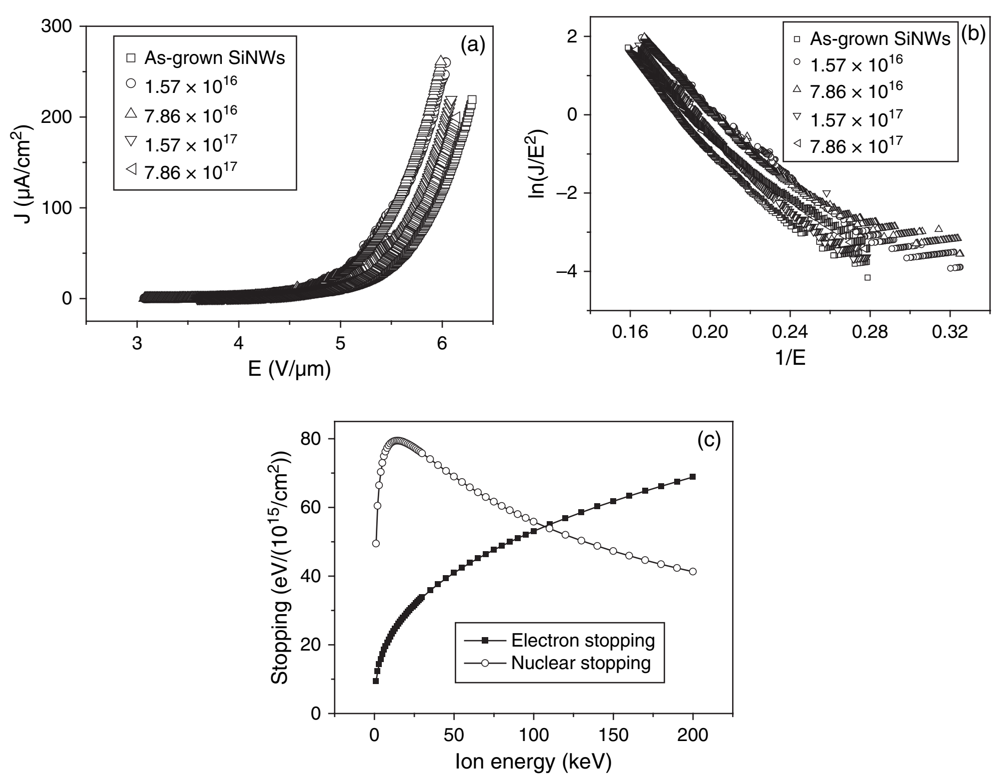

Fig. 3. (a) J–E plots of SiNWs with various ion irradiated doses; (b) F–N plots of SiNWs with various ion irradiated doses; (c) TRIM calculation of stopping effects of the Si ions irradiated SiNWs.

of the SiNWs and then emitted to vacuum. The existence of the defects makes the Fermi level shifting upward and the tunneling potential is thus reduced, which provides the convincing evidence for the improvement of the FE after ion irradiation.

Time stabilities of emission current density for the as-grown SiNWs and the irradiated SiNWs have also been determined. The testing data under 200 μA/cm^2 for ion irradiated SiNWs show that the standard deviation of emission current density after 7.86×10^{16}/cm^2 Si ion irradiation is only 7.19 μA/cm^2, which was much lower than 35.96 μA/cm^2 of the as-grown SiNWs; the current fluctuations of emission current density are in the range of $\pm$10.54% for the irradiated and $\pm$36.08% for the as-grown ones respectively. We can infer that the emission property is improved due to the formation of the amorphous SiNWs. However, with the doses increasing, the SiNWs were etched by the energetic ions beams so that the tips combined with each other, which would make the electron emission decline.

The J–E plots of the irradiated samples after post-annealing are illustrated in Figure 4. It can be seen that after post-annealing, the FE properties are further improved, where 850 and 1100 °C post-annealed samples with the same irradiated dose have the similar property, no matter for the dose of 1.57×10^{17} or 7.86×10^{17}/cm^2. After ion irradiation, plenty of defects including defect clusters could be formed in the nanowires. The defects could provide levels for electrons emitting while the defect clusters may restrain the electrons transferring. After annealing, the defect clusters are changed to simple defects and the restraint effect gradually eliminate, resulting to improvement FE properties.

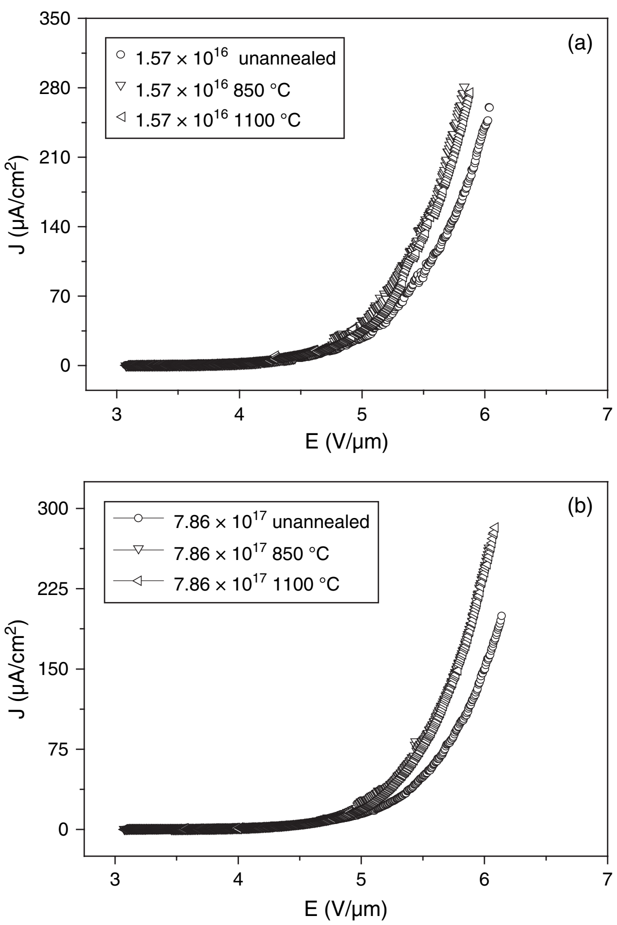

Fig. 4. J–E plots of the annealed implanted SiNWs. (a) 1.57×10^{16}/cm^2; (b) 7.86×10^{17}/cm^2.

4. CONCLUSIONS

Field emission characteristics of SiNWs have been enhanced by energetic Si ion irradiation. The Si ion irradiated SiNWs exhibit a relatively low FE turn-on field as 4.60 V/μm and the emission behavior dependent fairly on the F–N relationship in highly applied field region. The standard deviation of field emission current density of SiNWs irradiated with 7.86×10^{16}/cm^2 is 7.19 μA/cm^2, which was much lower than 35.96 μA/cm^2 of the as-grown SiNWs. The current fluctuation of field emission current density is in the range of $\pm$10.54% for the irradiated and much lower than $\pm$36.08% of the as-grown ones. The ion irradiation damage and the formation of amorphous Si structure are main reasons for the improvement of FE properties. All results indicate that SiNWs have advantages on integrated microelectronic field to fabricate microelectronic devices, especially in the field electron emitters.

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