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Field emission properties of discretely synthesized tungsten oxide nanowires

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ABSTRACT

We investigated the effect of the degree of dispersion of tungsten oxide nanowires on their field emission properties. We patterned tungsten films with $1 \times 1\ \mu m^2$ islands of various pitches (2, 5, 10, 20 and 30 μm) by electron beam lithography, sputtering and the lift-off technique, and then synthesized tungsten oxide nanowires on the islands. The number of nanowires per island was about 100. The sample with islands of 5 μm pitch exhibited the highest field emission current. We performed electrostatic simulations of an electric field around emitters (1 μm length) placed at various intervals. The simulation results had the same features as the experimental results.

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1. Introduction

Tungsten oxide nanowires are one-dimensional nanostructures, with diameters of 10–100 nm and a length of about 1 μm. Since the nanowires have high aspect ratios and are easily fabricated, they have attracted considerable attention as promising materials for field emitters of field-emission displays (FEDs) [1–4]. To date, it has been reported that straight tungsten oxide nanowires can be synthesized from sputtered tungsten films annealed in a vacuum furnace [3–7]. We have also demonstrated that the tungsten oxide nanowires obtained from sputtered tungsten films have good field emission properties [3]. The number density of nanowires was discovered to be an important parameter in determining the field emission properties [3]. A suitably low density resulted in good field emission properties owing to the concentration of the electric field [8]. Concentrating an electric field at the tip of tungsten oxide nanowires increases their emission current. Fig. 1a and b shows the schematics of electric fields around uniformly- and discretely-synthesized nanowires, respectively. In this study, we verified the degree of dispersion by patterning the tungsten thin films and then synthesizing nanowires on them. We also investigated the field emission properties of the nanowires.

2. Experimental

First, we sputtered a Cr film (300 nm thickness) on Si substrates. The film was formed by radio-frequency (rf) magnetron sputtering. The base pressure of the sputtering chamber was 1×10^{-2} Pa and the sputtering pressure was 5×10^{-1} Pa. This Cr film carried the emission current when we examined the field emission current of tungsten oxide nanowires. Second, we formed tungsten islands on the substrates by electron beam lithography, rf magnetron sputtering and the lift-off process. We used ZEP-520A (Zeon Corp.) as the electron beam resist (the thickness of the resist was 400 nm). We sputtered a W film (180 nm thickness) on the substrates. Ar gas was used as the sputtering gas. Third, we lifted off the tungsten films together with the resist using ZEP-A remover and carefully cleaned the samples with acetone and ethanol in an ultrasonic washing machine. The tungsten islands of $1 \times 1\ \mu m^2$ were patterned at intervals in an area of $5 \times 5\ mm^2$. We prepared five samples with island pitches of 2, 5, 10, 20 and 30 μm.

We placed the samples in a vacuum furnace and annealed them by infrared heating. The base pressure of the furnace was 2 Pa. Keeping a rotary pump on, we introduced O_2 gas. The flow rate of the gas was 1 SCCM. We annealed the samples from room temperature up to 550 °C for 3 min, and then maintained the temperature at 550 °C for 30 min. After annealing, we cooled the furnace to room temperature for 20 min while maintaining O_2 gas flow, then removed the samples from the furnace. The surfaces of the samples were observed by scanning electron microscopy (SEM; Hitachi SU-8000). Fig. 2 shows a SEM image of the tungsten oxide nanowires synthesized on the islands (island pitch: 2 μm). Their lengths were 600–1000 nm and the number of nanowires per island was about 100. In all kinds of samples, the nanowires were similarly synthesized on the islands. To investigate their field emission properties, the samples were set in a vacuum chamber through ITO glass and connected with a high voltage dc power supply. The gap between the samples and ITO glass was set at 70 μm. The base pressure of the vacuum chamber was 1×10^{-3} Pa.

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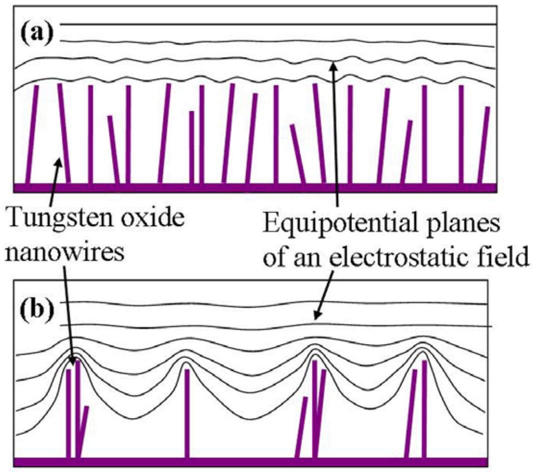

Fig. 1. Schematics of electric fields around (a) uniformly- and (b) discretely-synthesized tungsten oxide nanowires.

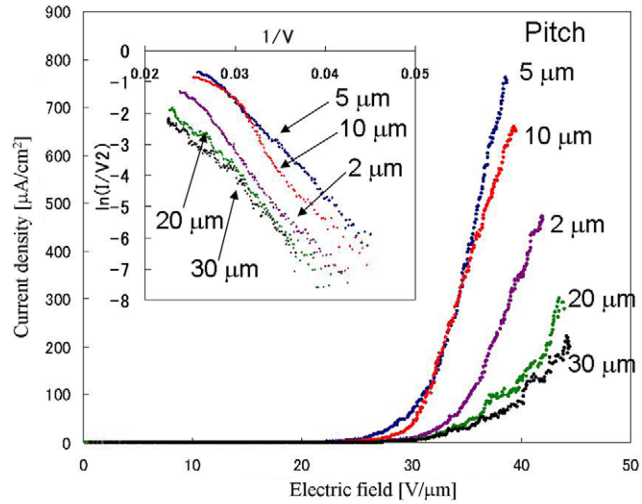

Fig. 3. (Color online) Current density versus electric field (I–V) plots for samples. The inset shows their Fowler–Nordheim (F–N) plots.

3. Results and discussion

Fig. 3 shows the current density versus electric field (*I–V*) plot and Fowler–Nordheim (F–N) [9] plot of the samples with the five different pitches (2, 5, 10, 20 and 30 μm). It shows typical field emission current density of the tungsten oxide nanowire cathode versus applied electron field characteristics for the diode configuration. The linear F–N plot indicates that the electron emission of tungsten oxide nanowires proceeded from a field emission process such as the tunneling of electrons through a potential barrier. Fig. 4 shows the current density at an electric field of 38 V/μm as a function of island pitch. This shows that the sample with 5 μm pitch emitted the highest current density of 690 $\mu A/cm^2$. In the samples with pitches of 10, 20 and 30 μm, the current density decreased as the island pitch became wider. From these results, we found that the sample having islands with 5 μm pitch had the highest field emission properties.

To verify our experimental findings, we performed finite element method (FEM) simulations of an electric field around parallel poles at various intervals, as shown in Fig. 5a and b (simulation software: ANSYS by ANSYS Inc.). We modeled poles with 1000 nm length, 20 nm diameter, and 20 nm apex. We obtained the strongest electric field at the tip of emitters in the simulation. Fig. 5c shows the electric field at the tip of emitters as a function of emitter pitch. The electric field became stronger as the emitter pitch became wider, and then the electric field converged when the emitter pitch was over 4 μm. From the results, we calculated an emission current for the various pitches of emitters following

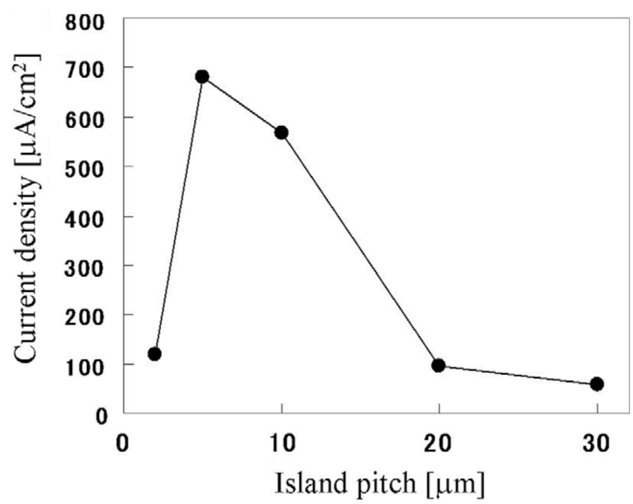

Fig. 4. Current density at electric field of 38 V/μm plotted as a function of island pitch.

the F–N law, then we assumed that the emission site density is proportional to the number of emitters [9]. Fig. 6 shows the calculated current density as a function of island pitch. The current density was the highest when the pitch of emitters was about 3 μm. It should be noted that the model in the simulation differs from the

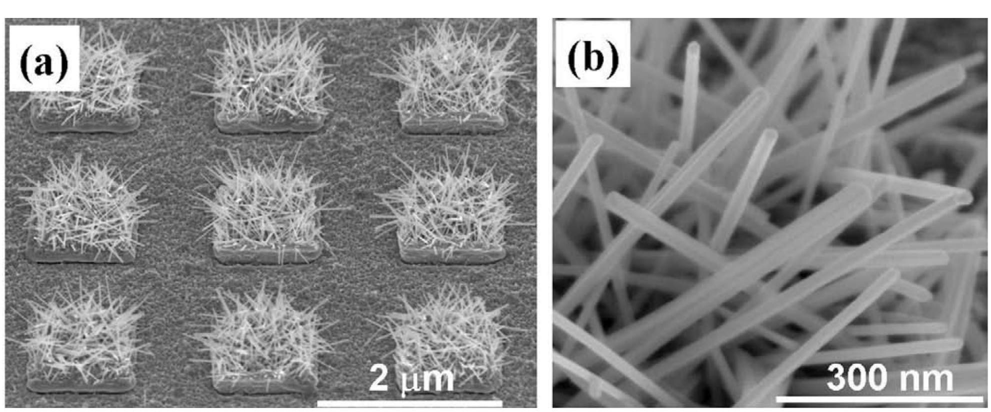

Fig. 2. (a) SEM image of tungsten oxide nanowires synthesized on islands (Tilt angle: 45°). (b) Enlarged SEM image of tungsten oxide nanowires.

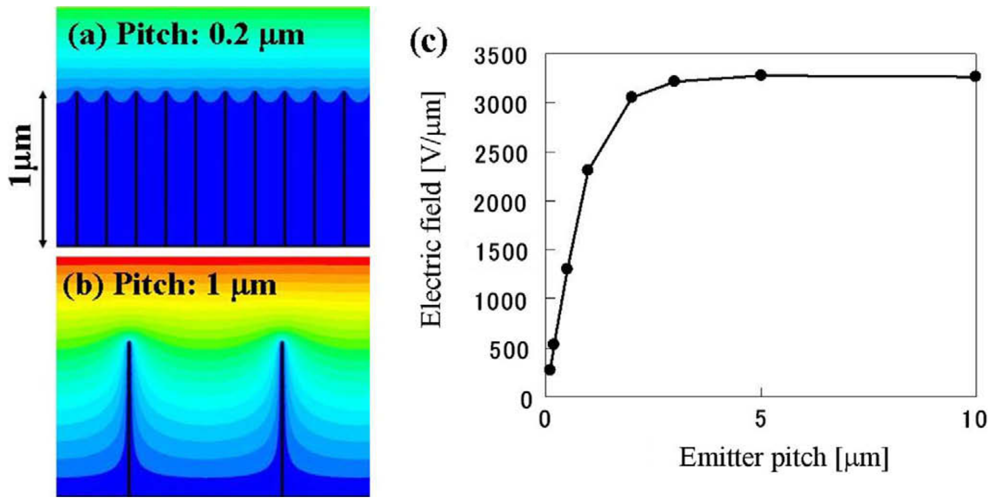

Fig. 5. (Color online) Simulation results of electric field profiles: (a) 0.2 μm pitch, (b) 1 μm pitch. (c) Electric field at the tip of emitters as a function of emitter pitch.

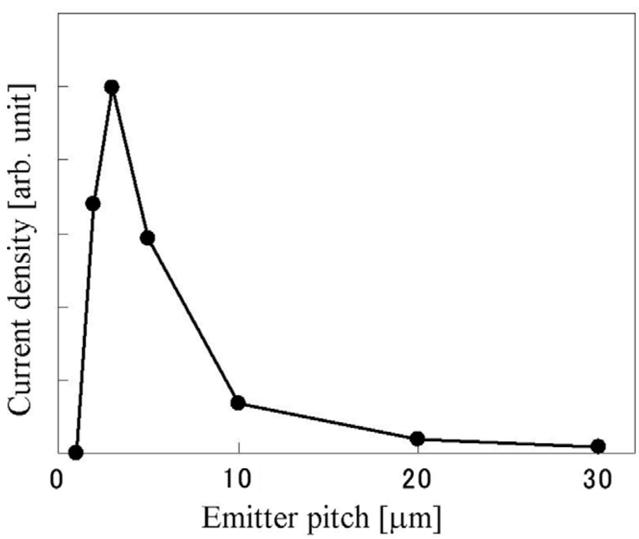

Fig. 6. Simulation results of current density as a function of emitter pitch.

actually synthesized nanowires on the islands. However, the calculation results had the same features as our experimental results. The electric field strength at the tip of emitters and the number of emitters greatly affect the field emission current density. The wider the emitter pitch becomes, the stronger the electric field at the tip of emitters. On the other hand, the wider the island pitch becomes, the fewer islands per unit area. Therefore, there is an optimum degree of dispersion of emitters for obtaining the highest field emission properties.

4. Conclusion

We investigated the effect of the degree of dispersion of tungsten oxide nanowires on their field emission properties. We synthesized tungsten oxide nanowires on $1 \times 1\ \mu m^2$ islands with various pitches. The lengths of tungsten oxide nanowires were 600–1000 nm and the number of nanowires per island was about 100. We found that the sample with the island pitch of 5 μm exhibited the highest field emission current among the samples with pitches of 2, 5, 10, 20 and 30 μm. We performed electrostatic simulations of an electric field around emitters (1 μm length) at various intervals. The simulation results had the same features as the experimental results.

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