

EFFECT OF LOW-ASPECT RATIO ON THE ENHANCED FIELD-EMISSION PROPERTIES OF DENSELY-PACKED Ni-NANOWIRE ARRAYS ELECTROCHEMICALLY GROWN THROUGH POROUS ALUMINA MEMBRANE

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Introduction

Field-emission (FE) properties of quasi-one-dimensional (Q-1D) nanostructures have recently gained tremendous interest in the FE display (FED) technology due to enormous geometrical field enhancement at the sharp emitter tips to provide necessary barrier field for cold electron emission under a comparatively low applied field (cf. Fig. 1a), thus having interesting applications in low-power panels (LPP) [1-3]. Arrays of Q-1D structures fabricated on rigid substrates can be used for FED, which is considered to be strong candidate for LPP applications because of thin profile, fast response, high brightness, wide operating temperatures and high production efficiency at lower cost [4]. But densely-packed, vertically-oriented nanowires/rods/tubes/pillars with high packing density show reduced FE properties due to the proximity screening effect proposed by Nillson et al. [5]. Fig. 1(b) schematically describes this effect between adjacent nanorods that significantly reduces the potential drop perpendicular into the substrate. Physically, higher packing density tends to increase the charge per unit area, thus increasing the electrostatic screening between neighboring nanorods and prevents the penetration of the applied field into the nanorods. This screening effect affects the local field enhancement at the emitter tips and increases the threshold field with a significant reduction in the overall FE current, as observed by various groups [6-8]. Inter-nanorod distance (d) and nanorod length (L) play important roles in the improved performance of the field emitters. Reportedly, $d/L=2$ produces optimal FE characteristics of nanorod arrays, which produces an ideal packing density for an array of average $1 \mu\text{m}$ long nanorods around 10^7 emitters/ cm^2 [5]. Hence, lower value of L would increase the effective packing density without compromising the optimal FE performance of the nanorod arrays. We have observed much lesser proximity screening effect in our densely-packed vertically-aligned Ni nanorod arrays of relatively lower aspect ratio, electrochemically fabricated on metal-coated Si substrate through porous alumina membrane (PAM). Due to lesser length of the nanorods, effective packing density increases with lesser electrostatic screening to show better FE properties even with higher packing density.

Experimental

Firstly, PAM is fabricated via constant current ($J=40 \text{ mA/cm}^2$) anodization process on a Ta-coated Si substrate under 0.3 M oxalic acid solution. Subsequently, Ni nanorods are grown through the nanopores of PAM in an electrochemical cell containing Watt's solution

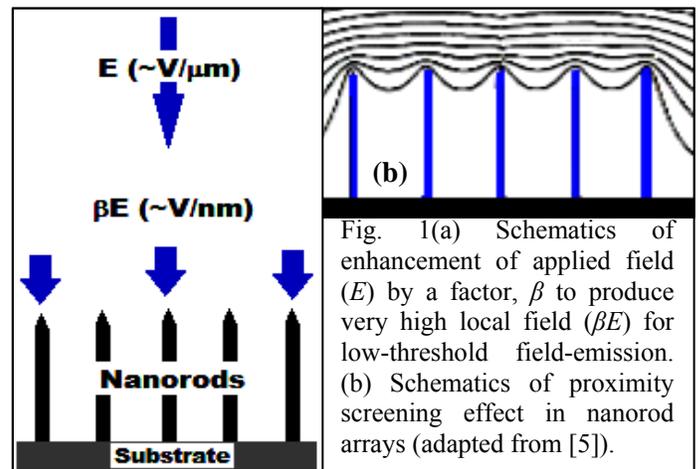


Fig. 1(a) Schematics of enhancement of applied field (E) by a factor, β to produce very high local field (βE) for low-threshold field-emission. (b) Schematics of proximity screening effect in nanorod arrays (adapted from [5]).

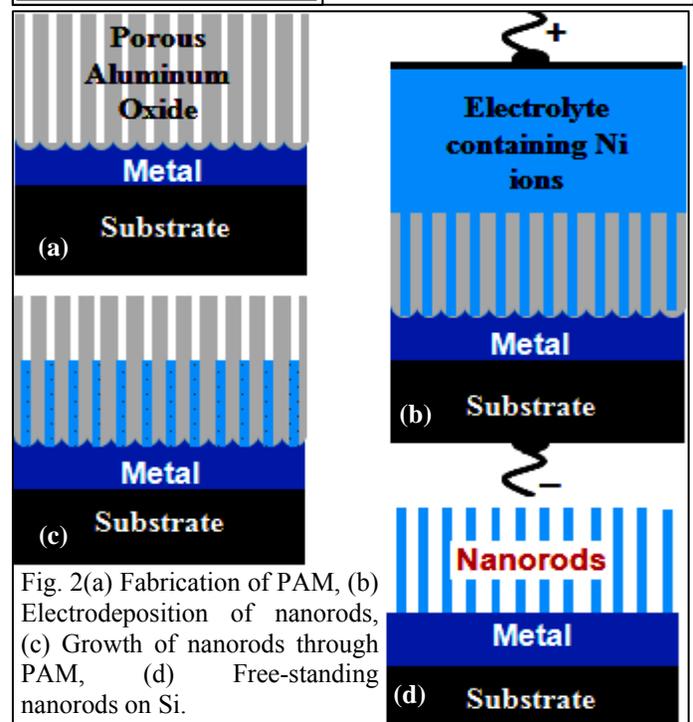


Fig. 2(a) Fabrication of PAM, (b) Electrodeposition of nanorods, (c) Growth of nanorods through PAM, (d) Free-standing nanorods on Si.

($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$, $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, and H_3BO_3) as Ni source under -1 V cathode potential (vs. Ag/AgCl) followed by wet-etching of PAM to get vertically standing Ni nanorod arrays on the substrate. Various deposition steps and parameters are described in Fig. 2 and Table 1.

Table 1 Summary of deposition processes

Process	Anodization of PAM	Ni Electrodeposition
Anode	Al/Ti-coated Si	Pt mesh
Cathode	Pt mesh	sample
Temp.	1°C	25°C
Dep. time	25 sec	60 sec

Results and discussion

Fig 3(a) shows the SEM image of uniform growth of the nanorods through PAM with length around 100 nm and inter-nanorod distance around 50 nm. Fig. 3(b) shows the AFM image of the top-views of the Ni nanorods after the removal of PAM depicting average nanorod diameter around 50 nm. Low aspect ratio of the nanorods is specifically maintained for three reasons. Firstly, non-uniform sealing of pores during Ni electrodeposition through PAM is reduced by taking lesser deposition time, which leads to smaller nanorod length but ensures highly uniform filling of nanopores to produce reproducible FE properties. Secondly, shorter length is chosen to increase the effective packing density of nanorods with lesser proximity screening effect, as stated earlier. For our sample with $d/L \approx 2$, the effective packing density is observed to be relatively much higher ($\sim 10^9$) to get enhanced FE properties shown below. Thirdly, lower aspect ratio with comparable axial and longitudinal dimensions of our as-synthesized nanorods lead to better field enhancement factor (β) as described by Zhang et al. [9]. Fig. 4(a) shows the emission current (I) vs. applied voltage (V) of Ni nanorod arrays with turn-on field around 5 V/ μm (defined as the applied field to get current density around $1 \mu\text{A}/\text{cm}^2$). Corresponding Fowler-Nordheim (FN) plot, shown in Fig. 4(b), fits well with straight line, indicating cold field electron emission within the nanorods. Slight deviation from linear fit of the FN plot is attributed to the fluctuations in the β -values imposed by the statistical variation of nanorod tip-dimensions, and also observed by others [7]. From the slope of the FN plot, β is calculated using known value of local work function of Ni nanorods ($\phi \sim 5.15$ eV [10]) and obtained as 4000 (β_{FN}), which is exactly same as calculated from ‘two-region-field-emission’ (TRFE) model [11] (β_{TRFE}). A comparison of the FE properties of our samples against previously reported values show that β is higher with comparable turn-on field and overall FE current although the packing density is more than two orders of magnitude higher than previous values. This is consistent with the model proposed by Zhang et al. [9], stated earlier, and clearly shows that the low aspect ratio with lesser nanorod length lead to better FE performance of our densely packed nanorods, and therefore, can become very useful alternative to the conventional field-emitters in FED technology.

Acknowledgement

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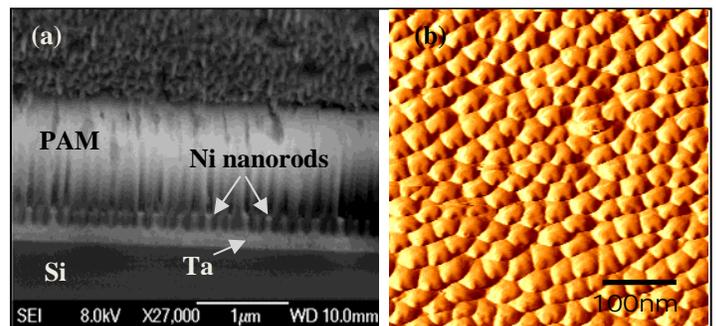


Fig. 3(a) Cross-sectional SEM image showing growth of Ni nanorods through PAM, (c) AFM micrograph of the top-view of Ni nanorods grown on Si substrate after removal of PAM. Average nanorod diameter is around 50 nm.

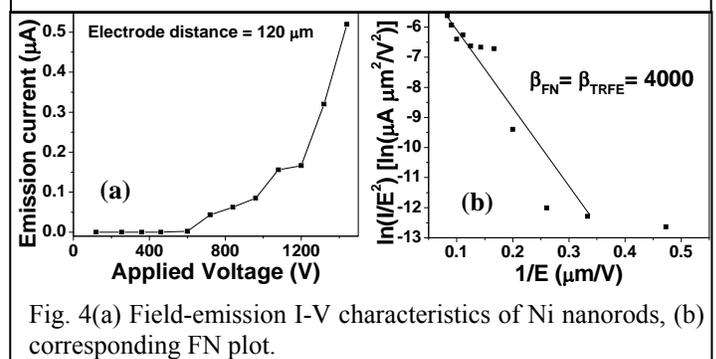


Fig. 4(a) Field-emission I-V characteristics of Ni nanorods, (b) corresponding FN plot.