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## The study of nano-scale field emission phenomena

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Advances in research into many vacuum microelectronics devices depend upon the realization of reliable high intensity electron sources. For this reason, the ability to fabricate uniform emitters is an important factor in many vacuum microelectronics applications, including their use as electron sources in various visualization equipment, flat panel displays, electron microscopy, microwave power devices, and especially for the fabrication of next-generation electron beam lithography. Over the past decade, field-emission properties have been studied extensively for various materials and geometrical arrangements, in which performance has been found to strongly depend upon the inherence, morphology, material density, and the sharpness, aspect ratio and surface conditions of the tip, to name a few. Recently, the advent of new nanofabrication techniques has led to the preparation of efficient electron emitters from various one-dimensional systems comprising different elements including hollow nanotubes, solid nanowires, coaxial cable structures, side-by-side biaxial nanowires, and nanobelts; that can deliver highly bright electron beams from a narrow energy spread. Therefore, how to design the easy fabrication, low cost, and high performance field emitter, to understand quantitatively the physical picture of a single field emitter or field emitters array participating in the field-emission process are very important topics. In our studies, first, in order to understand the physical picture of field emission phenomena, the field-emission characteristics of a single silicon nano-emitter were investigated by means of experiments and simulation models. The emitters array was fabricated by dry etching using inductively coupled plasma (ICP) through a three-step process. A novel experimental measurement technique by SEM with nanomotors including the constant voltage and the constant emission modes was developed. In the constant voltage mode, the tungsten probe was controlled by the nanomotor to measure the emission current to determine the approximate position where the maximum emission current occurs. In the constant emission mode, we moved the tungsten anode to measure the turn-on voltage at each position to find out where the minimum turn-on voltage occurs. By combining these two steps, we can precisely determine the 'right' position to measure the emission current from a single nano-emitter. Note that this novel technique can be adapted easily to measure the emission current from other types of nanoscale emitters. Accompanying these measurements, a parallelized 3D PIC code using the finite-element method coupled with a ray-tracing module was also developed and applied to simulate the field-emission process of single emitter. Besides, we also performed *in situ* field emission measurements on vacuum nanodiodes with a dynamically tunable nanogap, ranging from 20 to 150 nm. The nanogap was precisely controlled by a scanning tungsten probe attached on the nanomotor, thereby allowing the accurate and flexible three-dimensional FE characterization for silicon nanowire emitters (cold cathode). Our experimental results show that the local field enhancement factor and the onset voltage are sensitively dependent on the nanogap size, agreeing quite well with the theoretical fitting curve. Therefore, efficient and low-power driving FE nanodevices are envisioned by aggressively reducing the nanogap and squeezing nanodiodes. Finally, in order to explain the field emission properties of materials in nanoscale dimension, we put forward the quantum screening effect in field emission nanodiodes, explaining relatively low field enhancement factors due to the increased potential barrier that impedes the electron Fowler-Nordheim tunneling, which is usually observed in nanoscale FE experiments. We illustratively show this effect from the energy band diagram and experimentally verify it by performing the nanomanipulation FE measurement for a single P-silicon nanotip emitter ( $F=4.94\text{eV}$ ), with a scanning tungsten-probe anode (work function,  $F=4.5\text{eV}$ ) that constitutes a 75-nm vacuum nanogap. A macroscopic FE measurement for the arrays of emitters with a 17- $\mu\text{m}$  vacuum microgap was also performed for a fair comparison.

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