

trodes or conductive traces may be disposed alongside or upon the rear face of the emitter.

EXAMPLES

[0047] Silicon carbide wafers (6-H), of n-type doping with nominal resistivity ranging from 0.02 cm to 0.2 cm were etched into a porous nanostructures. A range of electrochemical conditions were explored, and the resulting structures are dependent on the specifics of the anodization chemistry. This difference in nanostructure morphology manifests itself in the emission characteristics, as it leads to different local field enhancement. As an example, FIGS. 4 and 5 demonstrate the variation in structure that result from wafers anodized using electrochemical solutions with different conductivity. In a first set of conditions referred to herein as Condition 1, the aqueous chemistry consisted of an anodizing solution comprised of 10% HF and 5% ethanol (by mass) with the balance distilled water. In a second set of conditions referred to herein as Condition 2, the anodizing solution comprised of 20% HF and 5% ethanol (by mass) with the balance de-ionized water. In both cases, ohmic contacts were made to the silicon-terminated side of the wafer by depositing 50 nm of Ni followed by annealing at 300° C. in Argon. The emitting or carbon-terminated side was subsequently anodized at 20 V using a Pt mesh counter-electrode. Both conditions yielded a nominal anodization rate of 4 $\mu\text{m}/\text{min}$, and porous structures approximately 90 μm in depth were readily produced. Wafers anodized using Condition 2 also had an undesirable dense top layer approximately 2 μm thick with low porosity, which was subsequently removed by reactive ion etching (RIE) using a plasma chemistry consisting of 90% SF_6 and 10% O_2 . As shown in FIG. 4, Condition 1 resulted in structures with wide variations in pore size, and pore wall thicknesses ranging from 30 nm to 200 nm, where the thicker pore walls dominate the structure. In addition, there is an insulating phase which manifests itself as bright spots in the figure. In Condition 2 shown in FIG. 5, more uniform porosity with smaller wall thickness were produced, with typical pore sizes of 150 nm and wall thickness between 20 nm and 30 nm. In FIGS. 4-5, the scale bar is 500 nm.

[0048] Performance of these emitters was characterized through testing using a large area diode configuration in a vacuum chamber with a base pressure of 1.3×10^{-7} Pa. Testing was typically performed at pressures above 1×10^{-6} Pa. The anode and cathode utilized parallel plate geometry and were approximately 1 cm in diameter, with electrode separation typically at $1.000 \text{ mm} \pm 0.002 \text{ mm}$. The measurements were performed either in continuous (dc) or pulse mode, with pulse widths ranging from 0.2 ms to 10 ms at 1 Hz. The emission results were independent of the testing procedure and pulse testing was primarily performed to reduce heating at the uncooled anode.

[0049] The thinner average pore walls of wafers processed through Condition 2 should lead to a higher local field enhancement and thus higher emission. This is indeed observed as shown in FIG. 6, where the emission characteristics corresponding to the etch conditions are plotted. For comparison, testing was also performed on an unprocessed wafer, demonstrating no significant emission. In both cases the emission areas are macroscopic, square-shaped with sides 2 mm in length. Here and in subsequent plots, the uncertainty in electric field is 0.2%, (1σ) and is determined by the uncertainties in the electrode separation and output of the high voltage apparatus. The uncertainty in the emission current is

0.1% (1σ) and is determined by the precision of the current measurement apparatus. In the Fowler-Nordheim plot shown in FIG. 7, β is inversely proportional to the slope, and the flatter line corresponding to Condition 2 indicates an increase in local field enhancement over Condition 1. The exact value of β requires detailed knowledge of the electron affinity or effective work function. For a wide-band gap semiconductor such as silicon carbide, electron affinity effects are significant and yield a reduced work function estimated to range from 3.6 eV to 4.2 eV, where the exact values are dependent on polytype, crystalline orientation, and nanoscale size. Combined, these factors lead to some uncertainty in Fowler-Nordheim analysis, and thus comparison of the field enhancement factors should be viewed qualitatively. With this caveat, the extracted β values for all tested devices are presented in Table 1, below. As shown, the field enhancement in Condition 2 is roughly a factor of two higher than that in Condition 1. These results demonstrate that it is possible to vary the density of emission points and local field enhancement through the electrochemistry conditions.

TABLE 1

Estimated β for Various Values of Work Function					
ϕ (eV)	Flat Cond. 1	Flat Cond. 2	Mesa	Fins	Pillars
4.2	393	732	770	936	1781
4.0	365	680	716	870	1656
3.8	338	630	663	806	1533
3.6	312	580	611	743	1414

[0050] Hierarchy at the second level is demonstrated by fabricating and testing structures with different large scale geometric dimensionality. To this end, the anodized structures initially were plasma-etched (RIE) into macroscopic mesas (2D) and further formed into line (1D) and point emitters (0D) using a high resolution focused ion beam (FIB) through gas-assisted ion etching. The nanostructured wafers anodized through Condition 2 were patterned by FIB etching using a Ga^+ ion source operating at 30 keV beam energy and 2.5 nA beam current, assisted by XeF_2 gas. The use of gas-assisted etching in shaping these emitter led to a six-fold increase in material removal rate, compared to etch removal without gas assistance. This efficient chemical removal of the silicon carbide in porous form enables straightforward formation of high aspect ratio structures and minimizes the amount of material re-deposited into emitter pores as a result of direct physical sputtering by the beam. This technique was used to fabricate a variety of exploratory structures, and assess the mechanical robustness and the limits of aspect ratio that could be achieved, as shown in FIGS. 1-3. Structures in the form of the un-patterned mesa, and arrays of fins and pillars were fabricated for emission studies and are illustrated in FIGS. 8-10. In these, the line (fins) and point (pillars) structures were formed from a starting macroscopic square mesa as shown in FIG. 8 with a side length more than ten-fold the pitch or the height of the emitter. This relative scaling is important for the measured current density to accurately represent larger sized arrays, and thus be macroscopic. Specifically, FIGS. 8-10 are SEM images of the noted structures. FIG. 8 illustrates a mesa, relative to a scale bar of 50 μm . FIG. 9 illustrates fins, relative to a scale bar of 10 μm . FIG. 10 illustrates pillars, relative to a scale bar of 50 μm . Corresponding J vs. E and F-N plots are provided in the insets of each