

[0023] FIG. 14 is a graph of current density versus electric field for the pillar projections of FIG. 10, taken to failure.

[0024] FIG. 15 is a planar view of a SEM image of an electrochemically etched “Si-face” of silicon carbide substrate formed using Condition 2.

[0025] FIG. 16 is a graph of current density versus electric field for the emitter shown in FIG. 15.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0026] The present subject matter is based upon a new form of field electron emitter, and particularly a cold field emitter, comprised of nanoporous silicon carbide (SiC) and fabricated using a wafer-based process. The resulting monolithic and porous silicon carbide surface emitters exhibit remarkable performance characteristics. Unlike previously known emitters, the present subject matter structure is free of nanostructured tubes or rods, and in contrast, is a rigid and homogenous porous structure. Significantly, the present subject matter emitters are capable of stable emission at macroscopic current densities comparable to thermal sources, allowing for their implementation in applications which require high emission current. Their emission properties are controlled by geometric enhancement of the electric field set by a two-level hierarchy of morphology: a local nanostructure and a larger scale global structure manifested through dimensionality. The combination of the intrinsic material properties and ability to control morphology at the two noted levels of hierarchy allows for optimization of critical parameters including emission, required field, and lifetime.

[0027] In contrast to thermionic emission in which electrons are released through heat, field emission extracts electrons using an applied electric field through quantum mechanical tunneling. In field emitters, electron emission is described by the Fowler-Nordheim model in which the tunneling barrier is distorted by a large electric field. Here, the emission current density is expressed by equation (1):

$$J \propto (\beta E)^2 e^{-\phi^{1.5}/(\beta E)} \quad (1)$$

in which the emission current per unit area is exponentially dependent on the emitter’s work function ϕ , the applied electric field E , and the field enhancement factor β . For arrays of emitters, β is defined by a two level hierarchy: 1) local electric field enhancement at the level of the individual emitting structure, determined by the size and shape of the local nanostructure, and 2) the global electric field enhancement, set by the larger scale spatial arrangement of the emitters comprising the array.

[0028] In accordance with the present subject matter, the fabrication process of these new emitters allows for control of this two-level field enhancement hierarchy and the ability to tune emitter characteristics. The emitters are fabricated from silicon carbide wafers. The wafers are electrochemically etched into a monolithic nanoporous structure and subsequently further processed by ion etching, while maintaining morphology and porosity, as illustrated in FIGS. 1-3. Specifically, FIGS. 1-3 are scanning electron microscopy (SEM) images of porous silicon carbide substrates demonstrating the two-level hierarchy set by local nanostructure and macroscopic morphology. In FIG. 1, pillars extending from a face of the silicon carbide substrate are shown relative to a scale bar of 10 μm . In FIG. 2, fins extending from a face of the silicon carbide substrate are shown relative to a scale bar of 50 μm . In FIG. 3, a magnified view of the fin projections of FIG. 2 are

shown relative to a scale bar of 4 μm . At the first level of hierarchy, field enhancement is defined by the shape of the local nanostructure, and varied through electrochemistry conditions to alter relevant features such as porosity and wall thickness. At the second level, the macroscopic shape of the structure controls the global field enhancement across the emitting area.

[0029] The starting material, silicon carbide, is chosen as it is refractory and capable of withstanding high current densities. In addition, silicon carbide possesses a wide electronic bandgap, and may be n-doped. This property leads to an enhanced tunneling probability and thus increased emission, by reducing the effective work function or electron affinity. A silicon carbide substrate of any poly-type can be used. It will be appreciated that other starting materials could potentially be used, such as for example gallium nitride. However, in no way is the present subject matter limited to silicon carbide or gallium nitride.

[0030] Additional details and aspects of the methods and field emitters of the present subject matter are as follows.

Methods

[0031] The methods of the present subject matter employ electrochemical etching, or “electroetching” or “anodization”, to form a porous and specifically, a nanoporous structure, in the silicon carbide substrate. Then, after formation of the porous matrix within the substrate and at least along one or more face regions of the substrate, the porous substrate is subjected to one or more operations to form a plurality of discrete emission projections extending from the face region (s) of the substrate. The discrete emission projections can be in a variety of different forms such as but not limited to pillars, fins, columns, “knife” like rows, or other shapes and configurations.

[0032] The electrochemical etching can be performed in a variety of different techniques and using various equipment and configurations. Generally, the silicon carbide substrate to be electrochemically etched is placed in electrical connection to a positive electrode or pole of a source of electrical current, and typically direct electrical current. A negative electrode is also provided and placed in electrical communication with the electrical source. A platinum electrode known in the art can be used as a negative electrode for facilitating electrical connection to the circuit and is immersed in the anodizing solution. The silicon carbide substrate is then immersed in an electrolyte or anodizing solution as described in greater detail herein. A voltage is then applied across the platinum electrode and the silicon carbide sample.

[0033] For certain versions of the present method, a voltage of from about 10 V to about 100 V has been found to be useful, with about 20 V being preferred. However, it will be understood that the present subject matter is not limited to any of these particular voltages.

[0034] The time period for which electrochemical etching is performed depends upon the desired characteristics of the field emitter such as size, density, and configuration of the pores and voids and the resulting porosity of the silicon carbide substrate. Typical time periods for electrochemical etching are from about 1 minute to about 8 hours, and more typically from about 5 minutes to about 4 hours, with 10 minutes being suitable for many applications. As previously noted, it will be appreciated that the present subject matter methods can be performed for time periods greater than or less than any of the noted time periods. Also, continuous and