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Field emission properties of Au–Si eutectic

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Abstract

Au–Si eutectic on the top of silicon whiskers demonstrated good emissivity at relatively low voltage. Both single tip emitters and arrays of tips were investigated. A maximum emission current of 300 μA was obtained from single-tip Au–Si eutectic emitters. Two possible emission mechanisms were considered: emission from edge-like protrusions on the surface or hot electron emission from Au–Si microjunctions.

1. Introduction

In addition to "classic" field emitters that are tips or arrays of tips with small radii of curvature, another approach to making field emission cathodes is fabrication of materials that could emit at low fields without intentionally-made regular highly curved surfaces. This approach is developed by Kierkpatrick et al., who reported the emission properties of biomolecular and $TaSi_2$–Si eutectic microstructures [1], by Willshow and Boswell [2] with porous silicon. Composite cathodes, comprising of a random mixture of insulative and conductive particles, were proposed by Bajic et al. [3] and by Christensen [4].

In this paper data on the emission properties of a Au–Si eutectic on the ends of as-grown vapor–liquid–solid silicon whiskers are presented.

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2. Experimental

Silicon whiskers were grown by the vapor–liquid–solid technique using gold as a eutectic-formed metal [5]. The as-grown whiskers were about 100 μm in height, and they had a Au–Si eutectic "cap" on the top (Fig. 1a). The diameter of the "cap" was several μm. Three different kinds of emitters were studied:

(1) Single-tip emitters grown on the butt-end of a Si rod $1 \times 1 \times 10$ mm^3 in dimensions. (The growth end of the rod was polished and etched in an HF–HNO_3 solution, the dimensions of the face after pre-growth preparation were approximately 0.5×0.5 mm^3.)

(2) 30 to 50 tip arrays grown on the Si rod, as described in (1) above (Fig. 1b).

(3) A multi-tip array grown on a flat Si substrate with dimensions 10×10 mm^2. The tip-to-tip separation in the array was 30 μm. The number of tips in the array was approximately 2×10^5.

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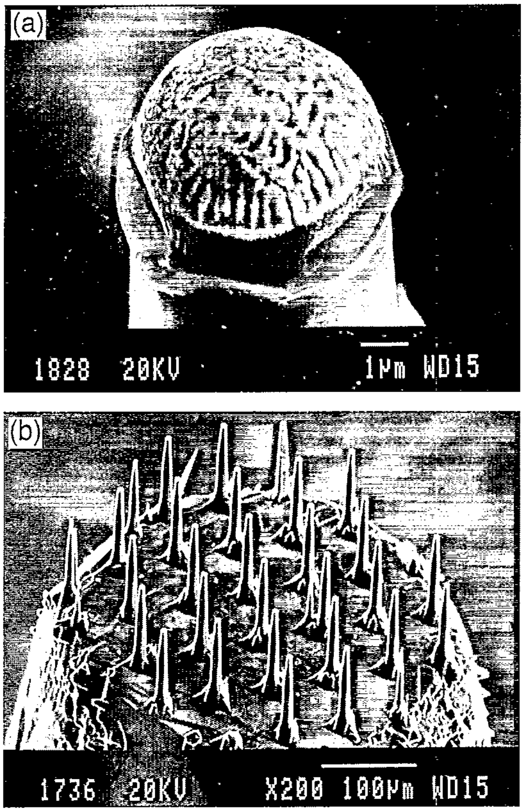

Fig. 1. SEM micrograph of a Au–Si eutectic "cap" on the top of a Si whisker (a), and an array of whiskers on a Si rod (b).

The field emission characteristics of both single-tip emitters and arrays on the rods were studied in an ion pumped system at a pressure of 10^{-8} Torr. The tip-to-anode distance was 100 μm. The anode was a stainless steel disk 50 mm in diameter. A multi-tip array on the flat substrate was tested as a sealed device prototype with anode-to-cathode separation of about 1 mm.

3. Results and discussion

3.1. *Field emission*

3.1.1. *Tips on the rod*

Current–voltage (I–V) and corresponding Fowler–Nordheim (FN) characteristics of a single-tip emitter and a 50 tip array are shown in Figs. 2a and 2b. From the general considerations based on the FN equation, measurable field emission currents from such blunt tips were no expected until the applied voltage was close to 10 kV. However, as can be seen from Fig. 2, emission started at several hundred volts. For different single-tip samples the starting voltage, corresponding to an emission current of 0.1 nA was between 600 and 1500 V. Emission currents of tens μA were achieved at voltages below 2 kV. A maximum current of approximately 300 μA was obtained from a single-tip emitter before the tip's failure. Emission current fluctuations were from 20 to 60%.

In the case of "small" arrays on the rods, emission characteristics were shifted to the lower voltage region, and the total current from the array was approximately equal to the current from a single-tip emitter at the same voltage, multiplied by the number of tips in the array, i.e. additivity of the emission current took place.

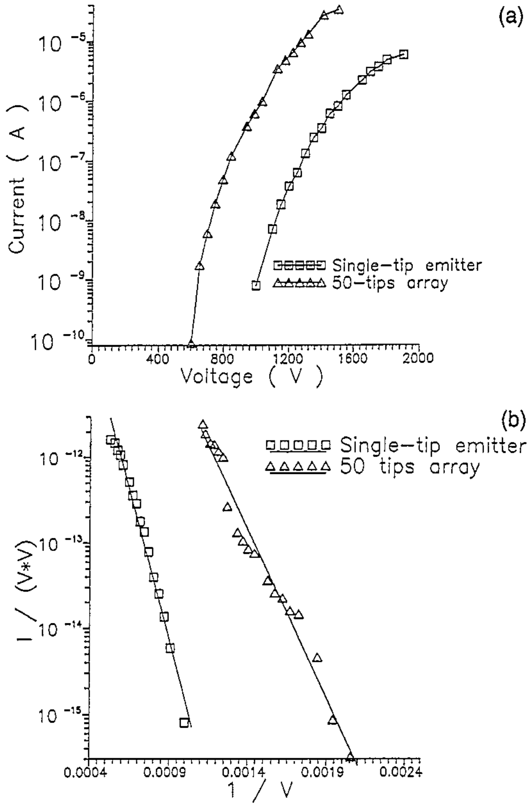

Fig. 2. I–V (a) and FN (b) plots of a single-tip emitter and 50 tip array.

3.2. Multi-tip array on a flat substrate

Based on the good emission properties of single-tip emitters with Au–Si eutectic "cap", and on the additivity of the emission current of a "small" array, an attempt was made to fabricate a high-current-density cathode for RF application. A sealed multi-tip array with about 2×10^5 emitters was tested for maximum current in DC mode. The I–V and FN plots of the array are shown in Figs. 3a and 3b. The emission current saturated at 2.5 mA and remained at the same level on further increase of the voltage. The FN plot of the array in the non-saturation region is non-linear (Fig. 3b). This non-linearity can be explained in terms of a statistics model for multi-tip arrays proposed in Ref. [6]: behavior of the plot similar to that in Fig. 3b was predicted in the model.

In contrast to the "small" array, the emission current of multi-tip arrays was not additive. The non-additivity of emission current of multi-tip arrays is one of the most important problems of high-current-density FEAs (for example, for RF applications).

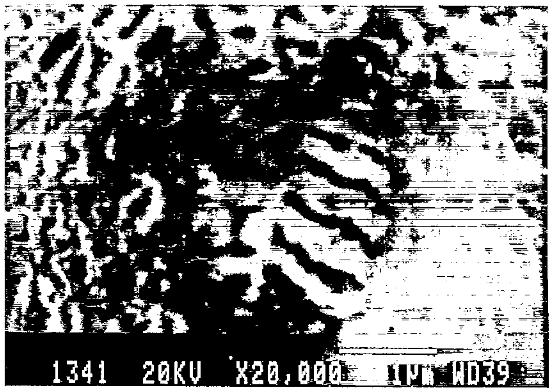

Fig. 4. SEM micrograph of the surface of a Au–Si eutectic "cap" at high magnification.

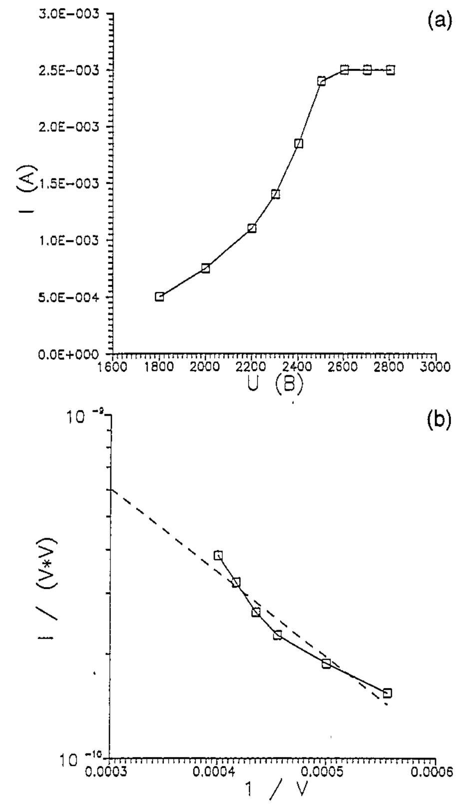

Fig. 3. I–V (a) and FN (b) plots of multi-tip array.

3.3. Emission mechanism

As already mentioned above, the blunt tips with radii of the curvature of several microns are not supposed to emit measurable current at voltages below tens of kV, if the FN emission mechanism and "normal" work-function of 4–5 eV are assumed. Formal implementation of the Fowler–Nordheim equation to Au–Si eutectic-based emitters gives a work-function less than 1 eV as a result. This value is out of the question, since the work-functions of both Si and Au are more than 4 eV. We suggested two possible emission mechanisms. The first is emission from the highly developed surface of the eutectic "cap". A scanning electron microscope (SEM) image of the surface at high magnification is shown in Fig. 4. Sharp edge-like protrusions may be suggested to be on the emitting surface. Field enhancement at these protrusions could effect field emission. In terms of this model, high maximum currents, achieved from Au–Si eutectic, can be explained due to the large number of emitting points randomly distributed around the emitter's surface (array effect), and due to the metallic nature of the top of the emitter (maximum currents of metal field emitters are known to be about an order of magnitude larger than that of silicon ones). The good emission stability may be due to the excellent chemical stability of gold (material effect) and/or due to averaging of the currents from individual emission points on the emitting surface (the array effect).

Another possible emission mechanism that can explain the apparently low work-function is hot electron emission from a number of microscopic Au–Si Schottky junctions. Additional experiments are necessary to make the emission mechanism more clear.

3.4. Additivity and non-additivity of emission current

Additivity of the emission current means that the total current of an array of the tips $I = I_{tip}N$, where I_{tip} is the current of a single-tip emitter with parameters identical to the tips in the array, and N is number of tips in the array. In practice, the current of a multi-tip array is non-additive, and is considerably less than $I_{tip}N$.

In our case, different results were obtained for two different arrays. The emission current of a "small" (50 tips) array on a "small" (0.5×0.5 mm) substrate is approximately additive, as can be seen from Fig. 2. However, maximum current experiments performed by using a "large" (2×10^5 tips) array on a "large" substrate (10×10 mm) demonstrated the non-additivity of the current. A possible explanation of these results is that current additivity depends on the number of tips in an array, and there is a critical number of tips N_c, at which the transformation from the "additive" emission mode to the "non-additive" one occurs. Another possibility to explain the difference in emission behavior of "small" and "large" arrays is different field enhancement conditions for the two arrays.

4. Summary

Field emission studies of Si whiskers with Au–Si eutectic "caps" on the top were performed. Both single-tip emitters and arrays of tips were investigated. Emission at relatively low voltage was observed. A maximum emission current of 300 μA was obtained from a single-tip Au–Si eutectic emitter. The observed emission effects can probably be explained in terms of surface edge-like protrusions or by hot electron emission from Au–Si microjunctions.

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