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ScienceDirect
Ceramics International 34 (2008) 971–977
CERAMICS INTERNATIONAL
www.elsevier.com/locate/ceramint

Si field emitter arrays coated with thin ferroelectric films

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Available online 2 October 2007

Abstract

This paper demonstrates novel approach on Si field emitter arrays (FEAs) coated with thin ferroelectric films for vacuum microelectronic applications, which exhibit enhanced electron emission behaviors. The films were deposited using sol–gel and sputtering process, respectively. In sol–gel approach, the emission behavior is highly correlated to the crystallinity of (Ba,Sr)TiO_3 (BST) layer. The interfacial reaction between Si and BST film would deteriorate the crystallinity of the films, and in turn impede the electron emission from silicon tips. The film thickness and the dopants also affect the emission behaviors significantly. In sputtering process, the nitrogen-incorporated $SrTiO_3$ (STO) films are deposited with eliminated interfacial due to relatively lower processing temperature. The enhanced emission characteristics are highly correlated with nitrogen-incorporation and film thickness. These encouraging results have offered great promise for the application of ferroelectric films in field emission devices.

Keywords: Field emission; Ferroelectric thin films

1. Introduction

Field emission (FE) is usually based on the physical phenomenon of quantum tunneling, in which electrons are injected from the surface of materials into vacuum under the applied electric field. Compared to thermionic cathode vacuum tubes, the field emission devices could offer some unique advantages, such as compact size, modest power consumption and possibility to integrate with solid-state electronics. They have a number of important applications both in military and domestic industries, including flat panel displays, microcolumns for electron beam parallel writing, various types of vacuum microelectronic devices, RF devices, vacuum sensors and space instruments [1]. To date, a variety of field emission cold cathode materials have been developed, including materials for microfabricated field emitter arrays, diamond and related films, quasi one-dimensional nanomaterials like carbon nanotubes and ferroelectric materials. Recently, the enhanced electron emission behavior from the $Ba_{0.66}Sr_{0.33}TiO_3$ (BST)-coated silicon tip arrays was discovered by Kang [2,3] and Zhu [4]. BST is a well-known material in ferroelectric family. However, the emission current from BST film surface is different from the so-called ferroelectric electron emission (FEE). It is known that FEE is an unconventional electron emission effect [5,6] and generated by a deviation of spontaneous polarization from the equilibrium state under pyroelectric, piezoelectric effects, or polarization reversal. In contrast, the emission current from BST thin films demonstrates a steady state current and is much similar to the classic types of electron emission from the solids. The emission behavior is found to be highly correlated with their structure [2,3] and stoichiometric composition [4]. In this paper, we summarize our recent advances on the enhanced field emission of BST films coated on microfabricated Si field emitter arrays (FEAs) via sol–gel and sputtering process. Moreover, a series of structural studies for understanding the corresponding mechanism is given also.

2. Field emission from BST thin films

Firstly, Si FEAs were fabricated using conventional microfabrication techniques, like photolithographic patterning, silicon anisotropic etching, oxidation for tip sharpening, and

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0272-8842/$34.00
doi:10.1016/j.ceramint.2007.09.084

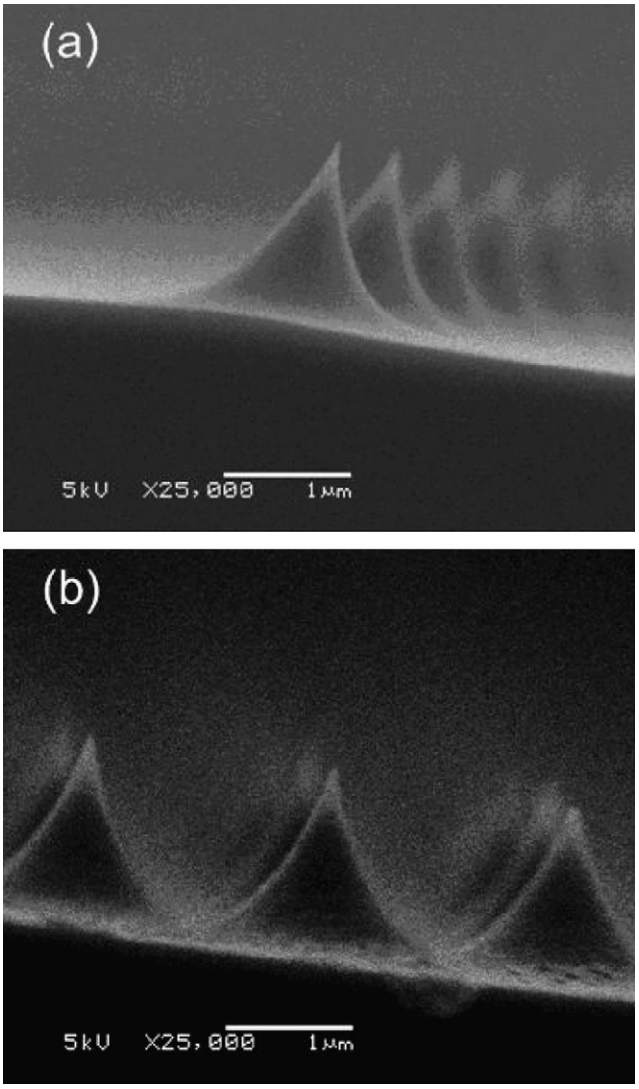

Fig. 1. SEM pictures (SEM) of (a) uncoated Si FEAs and (b) that coated with 30-nm-thick BST films.

buffered oxide etching. The *n*-type Si wafers with the resistivity of 2–5 Ω cm were used as FEA substrate and the tip height was controlled around 1 μm. Then, the BST thin films were coated on fabricated Si FEAs using sol–gel process detailed elsewhere [7]. Fig. 1 demonstrates the SEM pictures of the Si FEAs before (a) and after (b) BST coating. Field emission measurement was carried out in custom-made vacuum chamber with the vacuum up to 10^{-7} mbar, as shown in Fig. 2. A stainless steel base was used to make electrical contact to the Si FEAs, and an ITO glass with a sheet resistance of 10 Ω/□ was placed 50 μm above the cathode as an anode via a Teflon spacer. In the opened Teflon hole, around 10^4 tips were exposed for electron emission measurement. The threshold field was defined using an arbitrary criterion as the voltage required to produce a current of 1 pA per tip, corresponding to SNR over 1000.

It is observed that the field emission phenomenon of BST-coated Si FEAs is much sensitive to annealing temperature and film thickness as illustrated in Fig. 3 [7,8]. Such sensitivity is believed to originate from the structural feature of BST films. It is shown that the threshold electric field could be largely lowered from 36 V/μm for the bare Si FEAs to 19 V/μm for that with a 30-nm-thick BST coating annealed at 700 °C. The films annealed at 600 °C are amorphous in general with threshold field about 28.5 V/μm, and there is no encouraging improvement found due to its electric insulating nature. However, further increasing annealing temperature above 750 °C does not lead to further improvement in electron emission behavior. Instead, the interfacial reaction takes place at the BST/Si interface. The occurred interfacial reaction results in poorer crystallinity of BST layer, which might respond for the degradation of the electron emission behavior. Moreover, the thickness of BST layer also impacts on the development of perovskite grains in the films. The 15-nm-thick film on Si wafer is general in amorphous and the perovskite grains can be found in 30-nm-thick films. The measurement results indicate that the optimized thickness to achieve the lowest threshold field is around 30 nm. Moreover, BST-coated Si FEAs also demonstrated improved stability for electron emission. Fig. 4 compares the emission current stability of three

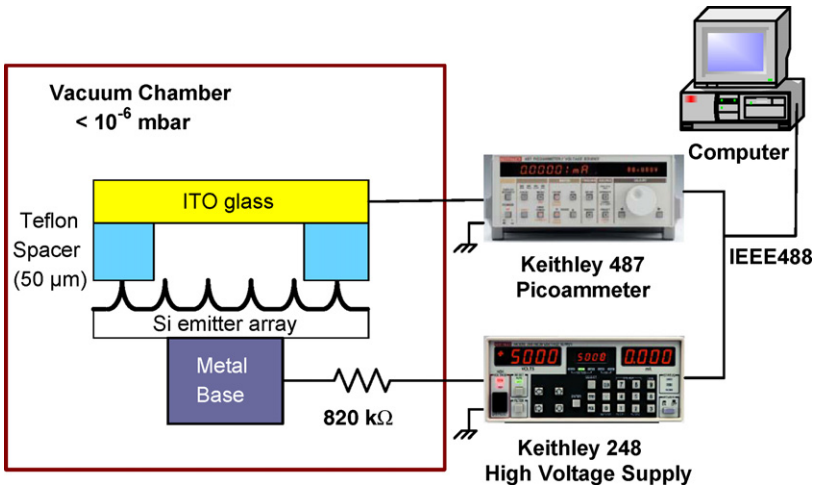

Fig. 2. Schematic diagram of the electron field emission characterization set up.