FABRICATION OF DIAMOND FIELD-EMITTER-ARRAY CATHODES FOR FREE-ELECTRON LASERS

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Abstract

Field-emitter arrays (FEAs) have several advantages as cathodes for free-electron lasers (FELs): they are rugged, require no laser driver, and generate little heat. We have developed two methods to fabricate diamond FEAs for FEL applications. In the first method, pyramids are formed on a Si substrate and sharpened by microlithography and then coated with CVD nanodiamond [1]. The advantages of this approach are a rigid, planar Si substrate, and microelectronic type fabrication. Typically, tip radii on the order of hundreds of nanometers are formed on 20 µm pyramids. In the second method, all-diamond pyramids are formed by a mold-transfer process in which they are sharpened by an oxide layer in the mold process. The diamond array is then brazed to a Mo substrate and the Si mold removed. The advantage of this process is that the tips are sharper, with tip radii smaller than 10 nm formed on 10 µm pyramids. The fabrication techniques and the performance of these cathodes will be discussed and compared.

INTRODUCTION

Recent experiments have demonstrated the potential of diamond field-emitter arrays as cathodes for free-electron lasers [2, 3, 4]. Diamond field emitters have several advantages over metallic devices. Since diamond is a covalent solid, temporal stability from clean diamond emitters is superior to that of metals. The high thermal conductivity of diamond mitigates self Joule heating which can lead to explosive vaporization of field emitters. Additionally, diamond emitters are chemically inert and perform well in poor vacuum conditions. In this report we describe the procedures for fabrication of diamond field-emitter arrays and diamond-coated silicon field-emitter arrays, and review the performance characteristics of each.

FABRICATION

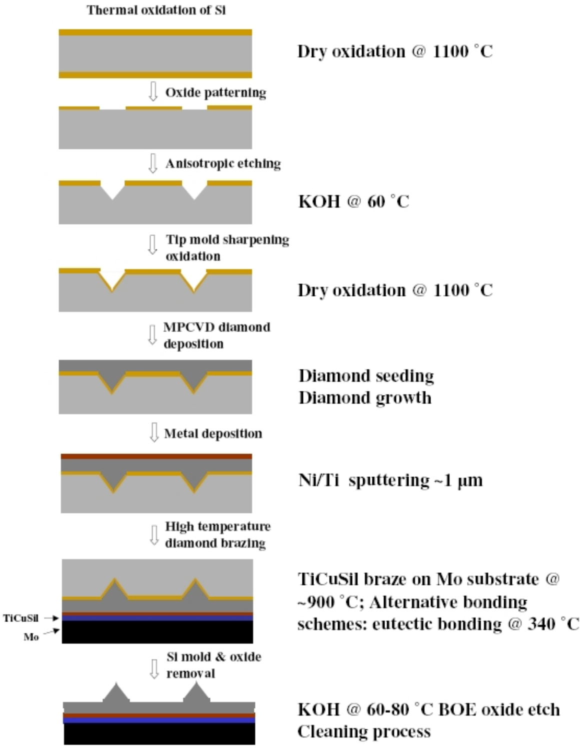

Figure 1. Diamond FEA fabrication procedure.

Diamond field-emitter arrays are produced using a mold-transfer process detailed in Figure 1. Oxidized Si wafers are patterned in preparation for an anisotropic KOH etch that produces pyramidal molds with an opening angle of 70°. These molds are sharpened by oxidation in preparation for diamond deposition. The oxide grows preferentially on the walls of the mold, avoiding the corners (Figure 2). The result is a sharp recess in the tip of the mold where the faces of the pyramid converge. By using mask holes that are slightly rectangular we can produce two sharp tips rather than a single. Over etching of the mold prior to oxidation allows production of quad-tip emitters.

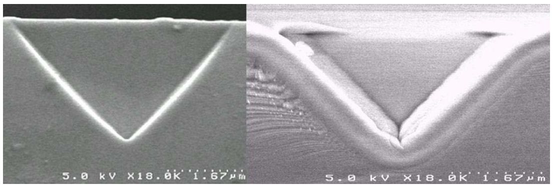

Figure 2. Si mold before (left) and after (right) oxide sharpening.

After sharpening, the mold is pretreated by ultrasonication in a diamond slurry, a step which provides nucleation sites for diamond growth. Diamond is then grown in the mold by microwave-plasma chemical-vapor deposition (MPCVD). A variety of growth recipes are used to achieve a desired combination of sp^2, sp^3, dopant concentration, and nitrogen content. A thin, conformal, nanodiamond layer is deposited first (Figure 3), while microdiamond is used to back fill the bulk of the structure.

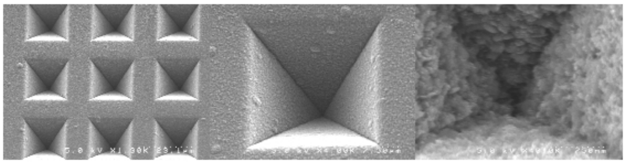

Figure 3. Conformal nanodiamond layer on Si mold prior to microdiamond deposition.

The diamond is then sputtered with a Ni/Ti coating that serves as a buffer/adhesion layer during substrate brazing. TiCuSil braze is used to attach the cathode-mold structure to a polished Mo substrate. After brazing, the protective Si mold is removed with a KOH etch, and the sharpening oxide is removed with a buffered oxide etch (BOE). Following standard cleaning procedures, the cathode is ready for testing. A completed diamond field-emitter array is seen in Figure 4.

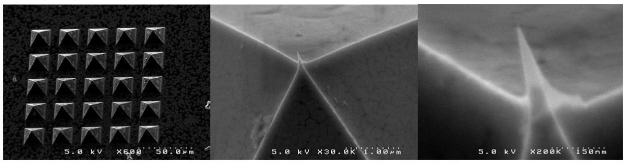

Figure 4. Completed diamond FEA with tip detail.

DC testing has shown diamond FEAs to be extremely rugged, having the ability to operate at very high per-tip current levels (> 15 μA DC) even in poor vacuum environments (~10^{-6} Torr). Procedures have been developed which enable self-limiting uniformity conditioning while maintaining low turn-on fields of ~5-7 V/μm.

A parallel FEA development program involves deposition of various types of CVD diamond on silicon microtip arrays. Silicon microtip arrays are produced by isotropic etching of a silicon wafer with a patterned surface oxide. Tips may be subsequently sharpened by a dry oxidation technique. The smooth silicon surface must be prepared for diamond growth by sonication in a diamond slurry. Prior to sonication, photoresist is spun on the array such that only the very tips are exposed. This ensures enhanced diamond nucleation on the tips during the growth process. Multiple diamond growth recipes have been used resulting in the different diamond structures in Figure 5.

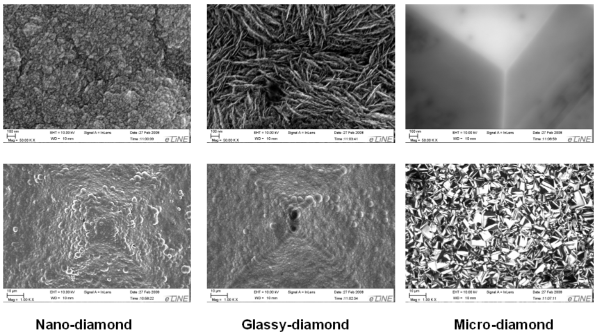

Figure 5. Diamond types from different growth recipes.

Thus far, it has proved difficult to grow thin conformal layers of diamond that maintain a small tip radius. Accordingly, field enhancement at the tip has been small and the required macrofields are prohibitively large for convenient testing in existing DC teststands. A coated Si tip is pictured in Figure 6. Once growth procedures are improved, the performance of different types of diamond can be examined.

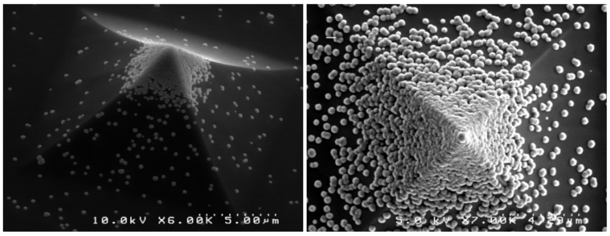

Figure 6. Nanodiamond coated Si tip.

CONCLUSIONS

We have presented an inverse-mold-transfer technique for the production of diamond field-emitter arrays. In DC testing we find these cathodes to have extraordinary properties [1] that demonstrate their potential for use in free-electron lasers. Fabrication procedures continue to be refined to improve production yield. Meanwhile, the development of diamond coated Si field-emitter arrays continues. The growth of very thin conformal films must be achieved before testing is possible in current apparatus.

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REFERENCES

[1] W. P. Kang, J. L. Davidson, M. Howell, B. Bhuva, D. L. Kinser, D. V. Kerns, Q. Li, J. F. Xu, J. Vac. Sci. Technol. B, **14**, 2068 (1996)

[2] J. D. Jarvis et al, *Toward Energy Spread Measurements of Diamond Field-Emitter Arrays*, these proceedings

[3] J. D. Jarvis et al, *Uniformity Conditioning of Diamond Field-Emitter Arrays*, these proceedings

[4] J. D. Jarvis et al, *Transverse Emittance of Diamond Field-Emitter Arrays*, these proceeding.