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ScienceDirect
Surface & Coatings Technology 201 (2007) 8120–8122
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Surface resistivity tailoring of ceramic insulators for an ion microprobe application

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Abstract

An important technique used for the grading of voltage drop along high voltage ceramic insulators is to provide some surface conduction to bleed off accumulated surface charge. We have used metal ion implantation to modify the surface of high voltage ceramic vacuum insulators to provide a uniform surface resistivity of order 10^{10} Ω/square. A vacuum arc ion source based implanter was used to implant Pt at an energy of about 125 keV to a dose of order 10^{16} ions/cm^2 into the surface of ceramic rods used to support the ion focusing system of the Columbia University high voltage ion microprobe. Here we describe the experimental set-up used to do the ion implantation and summarize the results of our exploratory work on implantation into test coupons and into the ceramic rods.

Keywords: Ion implantation; Surface resisitivity; Surface flashover; Metal ions; Ion optics

1. Introduction

The voltage hold-off capability of a high voltage ceramic insulator in vacuum is poor compared to that of the ceramic material or the vacuum itself. Electronic processes lead to a discharge over the ceramic surface commonly referred to as "surface flashover" [1]. The electrons originate from the negative end of the insulator assembly, most often at the "triple junction" (metal–ceramic–vacuum junction). The number of secondary electrons produced per incident primary electron can be high (about 10 for aluminum oxide at normal incidence) creating a net charge on the ceramic surface which increases the electric field gradient, and consequently the field-emitted current increases yet further. When the gradient exceeds the hold-off voltage in vacuum, surface flashover results.

Quite apart from concerns of flashover, charge buildup on the ceramic surface at voltage gradients lower than the breakdown field can lead to asymmetries in the electrostatic field in the vicinity of the charged insulator. In applications that call for a very high degree of electric field uniformity and symmetry, it is important that any charge buildup on the ceramic surfaces be small, and uniform.

Surface charge buildup may be reduced by adding a tolerable level of conductivity to the ceramic insulator surface. Materials such as chromium sesquioxide and vanadium pentoxide have been explored for the bleed coating, but it has been found that the surface resistivity obtained in this way varies widely, is non-uniform, and cannot be adjusted to target values. The technique of metal ion implantation of the ceramic surfaces has proved to be a successful alternative technology [2]. The ion implantation process is predictable and can be adjusted to target values during the process. Targeted surface resistivities of order 10–100 GΩ/square can be achieved to within a few percent, capable of dissipating several watts at 250 kV [3,4]. This approach has been used to advantage for grading the voltage drop along ceramic accelerator columns 25 cm I.D. by 28 cm long used at the Jefferson National Laboratory [4,5].

Here we describe the application of metal ion implantation for the grading of surface resistivity along the ceramic rods that support the electrostatic focusing system of the ion microprobe facility [6] at the RARAF (Radiological Research Accelerator

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doi:10.1016/j.surfcoat.2006.10.051

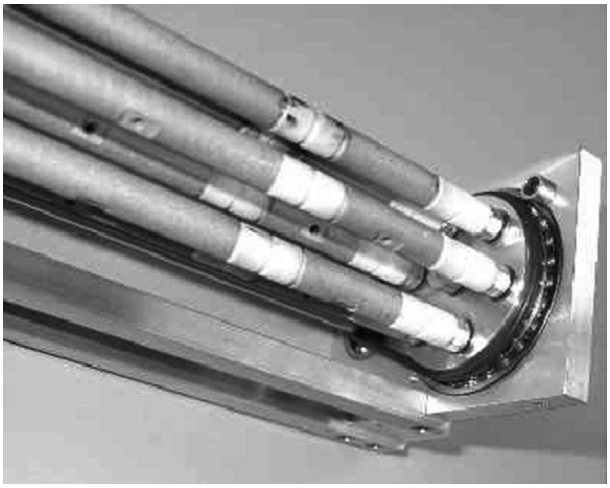

Fig. 1. Used, non-implanted, ceramic rods mounted on the implantation fixture. The base rotates slowly while the individual rods spin quickly on their axes so that the implantation is uniform.

Facility), Columbia University, which is used to study radiation effects on cells in culture [7]. The short probe-forming system is developed for the Columbia Microprobe that includes four electrostatic quadrupoles with a Russian quadruplet configuration. The sixteen electrodes that comprise the lens system are constructed along four 30-cm long rods that are 1.0 cm in diameter. Grooves defining the electrode and insulator sections are precisely cut in the surface at the appropriate locations. Insulating sections are 1.0 cm long with an additional groove to increase the conduction path. After implantation as described below, the insulated sections of the rods are carefully masked with Teflon tape and then the rods are sent to a commercial metallizer who applies a titanium adhesion layer and gold electrode surfaces using a sputtering technique. The completed rods are assembled into the lens system using ground and lapped titanium vee-block clamps and spacers to attain a final bore of 1.0 cm.

2. Ion implantation

Ion implantation of the ceramic rods that support the electrostatic quadrupole system was done both at LBNL (Lawrence Berkeley National Laboratory), Berkeley, California, and at HCEI (High Current Electronics Institute), Tomsk, Russia, using in each case a broad-beam vacuum arc ion source to produce high current Pt ion beams. The ion sources and implantation facilities have been described in detail elsewhere [8–11]. Briefly, the metal ion beam is produced in pulses of 250 μs duration at a repetition rate of several pulses per second. The mean energy of the beam ions, for the work described here, was about 125 keV, and the total extracted beam current several hundred milliamperes peak with a mean beam current less than this by the duty cycle of 1%. The vacuum pressure during implantation is in the low 10^{-6} Torr range. A magnetically suppressed Faraday cup that is temporarily moved into the beam path near the target location prior to beginning the implantation run is used to measure the beam current, and the required implantation dose is then accumulated by running for a pre-calculated number of beam pulses.

Implantation is done in a broad-beam mode. The diameter of the ion beam formation electrodes (“extractor grids”) is 10 cm and the initial beam diameter is almost the same. In this mode of ion implantation, the broad area ion beam propagates line-of-sight from ion source to target; there is no magnetic analysis or beam bending, and the target is implanted over its complete forward-exposed surface at one time, in contrast to the conventional swept, focused beam approach used widely in the semiconductor industry. At the location of the target the radial profile of ion beam current density is roughly Gaussian in shape with a FWHM that varies according to the ion source operating parameters and the source-to-target distance. Important also is that this facility and mode of implantation is accompanied by an ‘automatic’ charge neutralization feature — the broad area ion beam propagates in a self-produced sea of cold electrons that can provide more than enough neutralization for the potential charge build-up on the ceramic surface by the positive ion beam [12].

For the work described here we fabricated a planetary rotating facility in which a cluster of six ceramic rods was mounted, with each rod individually rotated as the cluster also rotated, held at such an angle that the entire surface of each rod was viewed by the implanting ion beam. Thus the rotating planetary holder held the rods at an appropriate angle (about 35°) to the incident energetic ion flux while continuously, slowly rotating them so that the entire rod surfaces were implanted. In this way the entire rod surface area was exposed to the beam and implanted, but in order to maximize the implantation dose symmetry and uniformity we turned the rods 180° lengthwise in their holder halfway through the implantation process. A photograph of the rods in the planetary holder is shown in Fig. 1.

The ceramic used was alumina with a surface finish of a few microinches rms roughness. Ion source extraction voltage was 60 kV, which for the Pt mean ion charge state [9] of 2.1 gives a mean ion beam energy of 125 keV; this corresponds to an ion

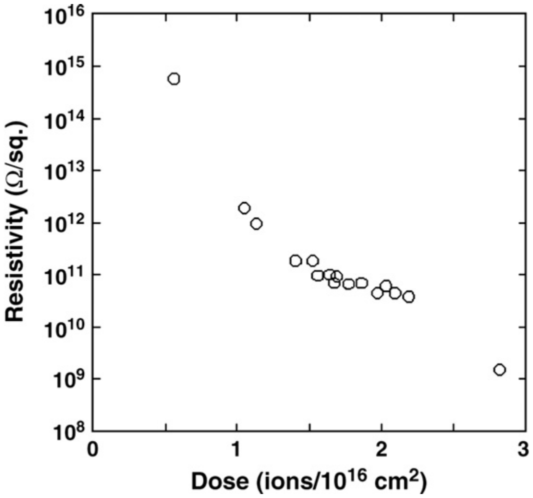

Fig. 2. Measured surface resistivity as a function of Pt ion implantation dose.

energy normal to the surface of about 70 keV. The source-to-target distance was about 1.5 m for this implantation set-up.

3. Results

The surface resistivity as a function of implantation dose, under conditions of the work described here, is shown in Fig. 2. The data point that shows an apparent rapid drop in resistivity as a function of applied dose seems to be real; we speculate that resistivity tailoring by ion implantation is a complicated physical phenomenon that may lead to a highly non-linear resistivity vs. dose relationship, and that considerably lower resistivities than achieved (or wanted) here may be obtainable. We do not have a detailed model of the conductivity mechanism, but the observed negative resistance coefficient with respect to temperature leads us to speculate that the mechanism is a semiconductor effect.

We have measured the resistance of 36 gaps on 6 rods implanted in two batches, using 1000 volts for the measurement. We find an average value of 150 GΩ with a standard deviation of 35%. As expected, most of the variation is between locations on the rods and between batches, with only 13% standard deviation among gaps at the same level in one batch. Using an effective length of 1.4 cm and diameter of 0.9 cm we obtain a value for the resistivity of 300 GΩ/square.

We have not measured the Pt ion implantation dose or profile in the alumina. Measurement in the usual way, by using RBS, is compromised by the surface roughness of the alumina, but we can make a good prediction of the profile using the SRIM code [13], which carries out a Monte-Carlo calculation of the stopping and range of ions in matter. For Pt into alumina at 70 keV, the range (distance below the surface to the peak of the distribution) is 220 Å and the straggling (HWHM of the distribution) 44 Å.

4. Conclusion

The assembled quadrupole lens system works as predicted, providing a focused beam spot with 2 μ diameter. It is capable of operation at 25 kV with minimal conditioning at startup, An earlier prototype with untreated insulators took many days to condition and would become noisy at 12 kV and failed at 15 kV.

Metal ion implantation provides a means for tailoring the surface resistivity of ceramic high-voltage insulators. Resistivity values in the range of several tens or hundreds of GΩ per square can be obtained, ensuring a remedy against charge buildup on the electrostatic quadrupole insulators and associated high voltage flashover problems. We are now building a pair of quadrupole triplets which will operate in series to yield a sub-micron diameter beam spot.

Acknowledgements

This work was supported in part by the U.S. Department of Energy, Office of Energy Research, under Contract No. DE-AC03-76SF00098, and in part by the National Institutes of Health under Grant No. P41 EB 002033.

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