A METHOD OF PRODUCING VERY HIGH RESISTIVITY SURFACE CONDUCTION ON CERAMIC ACCELERATOR COMPONENTS USING METAL ION IMPLANTATION

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Abstract

An important technique used for the suppression of surface flashover on high voltage DC ceramic insulators as well as for RF windows is that of providing 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 approximately 5 x 10^{10} Ω/square. A vacuum arc ion source based implanter was used to implant Pt at an energy of about 135 keV to doses of up to more than 5 x 10^{16} ions/cm^2 into small ceramic test coupons and also into the inside surface of several ceramic accelerator columns 25 cm I. D. by 28 cm long. 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 as well as the implantations of the actual ceramic columns.

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 is high (≈10 for aluminum oxide at normal incidence) creating a net positive charge on the ceramic surface which increases the electric field gradient. Consequently the field-emitted current increases yet further. When the gradient exceeds the hold-off voltage in the vacuum, surface flashover results.

After design measures used to reduce flashover such as polished corona rings are exhausted, flashover onset may be further retarded by adding a tolerable level of surface conductivity to the ceramic to bleed the charge away. The Photo Emission Electron Gun [2] for the Injector Test Stand at Thomas Jefferson National Accelerator Facility (Jefferson Lab) requires the application of this technique.

The design voltage for the gun is 500 kV. Two ceramic insulating cylinders, in series, 28 cm in length by 25 cm I. D. are used to stand off this voltage. Most methods for producing bleed coatings do not have high enough resistance for use at these very high electric fields. The excessive energy dissipated would heat the ceramic to unacceptably high temperatures. The coatings on insulators (Figure 1) in the photo emission gun are limited to resistances at the tens of Giga-Ohm level.

Figure 1
Ceramic Insulating Cylinder

In an earlier version of the gun, a chromium sesquioxide, vanadium pentoxide system [3] was used for the bleed coating. For all insulating cylinders using this process, we found that the resistance values varied widely, were nonuniform and were not able to be adjusted to target values. The technique of metal ion implantation of the ceramic surfaces[4] proved to be a successful alternate technology. The ion implantation process was generally predictable and could be adjusted to target values during the process.

2 ION IMPLANTATION

An LBNL broad-beam, multiple-cathode, vacuum arc ion source was used to produce Pt ion beams for the implantations discussed here. The source and implantation facility have been described in detail elsewhere [4-7]. Small implantation targets can be mounted on a radially moveable target holder. 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. Briefly, in typical operation, the metal ion beam is produced in pulses of 250 or 500 µsec duration at a repetition rate of several (typically 1 to 20) pulses per second. The mean energy of the ions in the beam is usually in the range 50-150 keV, and the beam current

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delivered to the downstream target is several hundred mA peak with the mean on-target beam current less than this by the chosen duty cycle, typically of order 1%.

Note that the 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. Important also is that this facility and mode of implantation are 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 [8].

Figure 2, Rotisserie Detail with Ceramic Insulating Cylinder in Implanting Position

For the work described here we fabricated an appendage to the implanter in which the ceramic insulating cylinder was housed and which allowed the cylinder to be continuously rotated while implanted. A rotating cradle (the "rotisserie") held the cylinder at an appropriate angle (35˚) to the incident energetic ion flux while continuously, slowly rotating it about its axis so that the entire inside surface was implanted. The mechanism was insulated and high voltage resistance was monitored at selected times during the processing. For this geometry the entire surface area of the cylinder was exposed to the beam and implanted, but in order to maximize the implantation dose symmetry and uniformity we turned the cylinder 180˚ lengthwise in the cradle halfway through the implantation process.

The type of ceramic used throughout this work was 97% alumina with a surface finish of a few micro inches rms. Ion source extraction voltage was 65 kV, which for the Pt mean ion charge state [6,9] of 2.1 gives a mean ion beam energy of 135 keV. Note that for the 55˚ angle of incidence, the ion energy normal to the surface is 135cos35˚ or 77 keV. The source-to-target distance was ~2.5 m for this implantation set-up.

The dc surface resistivity of the samples was measured using a 0-100 kV high voltage power supply and a current meter accurate to a few pA; most of the measurements were done with the sample (either small ceramic coupon or the actual cylinder) in vacuum, and at a voltage gradient of from 1 to 10 kV/cm.

3 RESULTS

We first investigated the effect of implantation parameters on the surface resistivity of small ceramic coupons of dimension 1 cm x 2 cm. The metal ion species investigated were Ti, Au and Pt; ion energy was varied from 50 keV to 135 keV; dose was varied from 1×10^{14} cm^{-2} to 5×10^{16} cm^{-2}; and the angle of incidence of the ion beam upon the ceramic substrate was either 0˚ (i.e., normal incidence) or 45˚; not all cells of this parameter array were tested. The most important and quite basic result from this preliminary exploration was that indeed the surface resistivity could be controlled in this way. Small surface cracks in the ceramic coupons, possibly introduced in the grinding stage of sample preparation and not at all easily visible in the unimplanted ceramic, were found to be a frequent cause of apparent irreproducibility; Interestingly, the cracks were considerably more visible after implantation. The dependencies of the resistivity on ion species, ion energy, and angle of incidence were small (over the range investigated), and the resistivity decreased with increasing implantation dose.

After the work on samples, we chose to do implantation on the cylinders using Pt at 135 keV, and to mount the cylinder at the angle required so as to expose the entire inner surface to the beam. Platinum does not oxidize and is a good cathode material for the vacuum arc ion source. Our small samples indicated (with much scatter) that Pt was slightly more effective than the nearest competitor, gold. Future work would certainly address further the issue of the effect of implanted species.

The surface resistivity as a function of implantation dose, under the conditions of the cylinder implant, is shown in Figure 3. In this processing we monitored the total number of implantation pulses, and the dose as shown in the figure is estimated from the pulse count based on RBS (Rutherford Backscattering Spectrometry) measurements [10] of the Pt dose implanted into small silicon coupons mounted in place of the cylinder during a calibration run. The required resistivity of approximately 50 GΩ/square was achieved for a dose of about 2×10^{16} $ions/cm^2$. The data point in Figure 3 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 (and wanted) here may be obtainable. No knowledge of the conductivity mechanism exists, but a negative resistance coefficient with respect to temperature leads to speculation that the mechanism is a semiconductor effect.

We have not measured the Pt ion implantation dose or profile in the alumina. Measurement in the usual way,

by using RBS, is not feasible because of the surface roughness of the alumina, but we can make a good estimate of the profile using the TRIM code [11], which carries out a Monte Carlo calculation of the transport of ions in matter. For Pt into alumina at 77 keV, the range (distance below the surface to the peak of the distribution) is 220 Å and the straggling (HWHM of the distribution) is 44Å

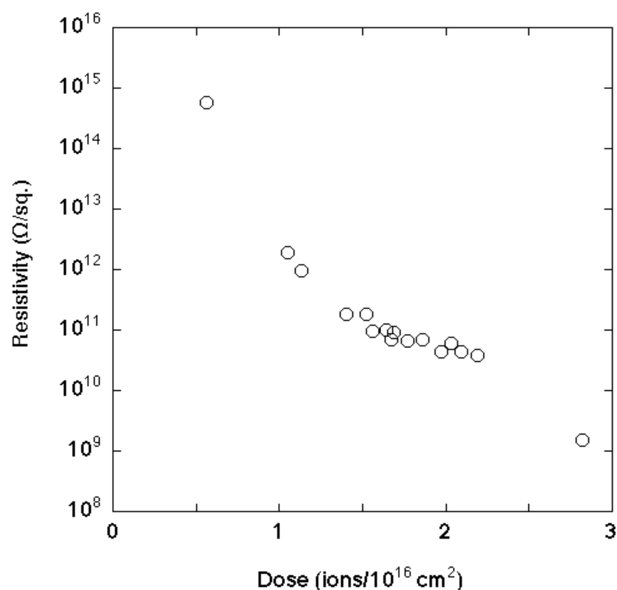

Figure 3 Resistivity vs. Dose

Three "production" cylinders were implanted. Each acquired nearly the desired resistance at 18 GΩ +- 5% (54 GΩ/square). A negative temperature effect was observed with a rise in resistivity of 50% upon cooling from the 60 C implantation temperature to room temperature. The resistance at 20 C should dissipate 3.5 W per cylinder at design voltage, well below a power that could cause a thermal run-away. Two cylinders have been assembled into an insulating column assembly, installed in the gun, baked out at 250 C for several days and subsequently conditioned up to 420 kV. In situ resistance measurement of one cylinder, with vacuum on the inside and room air on the exterior, yielded a value of approximately 13 GΩ. The nearly 1/3 drop is considered an effect of the conditions of measurement and attachment. No voltage dependence was seen in the in situ measurements using voltages of 10 to 100 kV.

Using a conservative approach, the gun has subsequently been run at 350 kV for collection of a data set at this value. (Before upgrade to the new ceramic insulating cylinders, the data sets were taken at 250 kV and 300 kV.) Conditioning the gun at 500 kV+ and operation at 500 kV awaits production of a spare ceramic cylinder set and success at intermediate voltages.

4 DISCUSSION AND CONCLUSION

Unlike the original methods tried, Metal Ion Implantation achieved the goal of obtaining the tens of GΩ value resistance required. The accuracy achieved was of a different class than the original methods, far more accurate because of the ability to monitor the decreasing resistance during the process. The method is also well suited to be the final process in a production sequence, where risky value-added features are already applied to ceramics before this high-value-added step. Note that before the continuous resistance monitoring feature was installed on the rotisserie, an implantation attempt undershot the target resistance. The cylinder was recovered to original condition by a simple sanding with diamond grit. The ion implantation method also appears to be well suited to the gun application, withstanding the bakeout and exhibiting no voltage dependence. However, more running experience would allow a firmer statement. The steep negative temperature dependence could result in thermal runaway for applications that have too low initial resistance and inadequate cooling. The investment in hardware and experience is now substantial and the ion implantation group at LBNL is ready to use this method in other applications.

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