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NOVEL TECHNIQUE ION ASSISTED IN-SITU COATING OF LONG, SMALL DIAMETER, ACCELERATOR BEAM PIPES WITH COMPACTED THICK CRYSTALLINE COPPER FILM*

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Abstract

To alleviate the problems of unacceptable ohmic heating, a magnetron mole with a 50 cm long cathode was designed, fabricated and successfully operated to copper coat a whole assembly containing a full-size, stainless steel, cold bore, RHIC magnet tubing connected to two types of RHIC bellows, to which two additional pipes made of RHIC tubing were connected. To increase cathode lifetime, movable magnet package was developed, and thickest possible cathode was made. The magnetron is mounted on a carriage with spring loaded wheels that successfully crossed bellows and adjusted for variations in vacuum tube diameter, while keeping the magnetron centered. An umbilical cabling system, which is enclosed in a flexible braided metal sleeve, is driven by a motorized spool and utilized to feed electrical power and cooling water. Although great progress was made with *in-situ* copper coating, by magnetron sputtering, to address the high room temperature resistivity, literature indicates that conventionally deposited thick copper films do not retain the same RF conductivity at cryogenic temperatures, since straightforward deposition tends to result in films with columnar structure and other lattice defects, which cause significant conductivity degradation at cryogenic temperatures. We utilize energetic ions for Ion Assisted Deposition (IAD) to reduce lattice imperfections, for coating. A IAD system for in-situ coating long small diameter tubes with compacted crystalline structure thick copper films has been developed. Moreover, development of techniques and devices can resurrect IAD for other applications, which have been impractical and/or not viable economically. Comparison of conductivity at cryogenic temperatures between straight magnetron physical vapor deposition and IAD may be presented.

INTRODUCTION

High wall resistivity in accelerators can result in unacceptable levels of ohmic heating or to resistive wall induced beam instabilities [1]. This is a concern for the RHIC machine, as its vacuum chamber in the cold arcs is made from relatively high resistivity 316LN stainless steel. This effect can be greatly reduced by coating the accelerator vacuum chamber with Oxygen-Free High Conductivity copper (OFHC), which has conductivity that is three orders [2, 3] of magnitude larger than 316LN stainless steel at 4 K. Previously, it was demonstrated [4] that deposition of even 5 μm of copper on RHIC tubing can result in room temperature conductivity, which is very close to solid copper. RF resistivity measurements [5, 6] were performed on 32 cm long RHIC stainless steel tubes coated with 2 μm, 5 μm, and 10 μm, thick OFHC with a folded quarter wave resonator structure. Q values were measured for eight resonant modes in the range of 180 MHz to 2 GHz, from which conductivity values were deduced. Those measurements [5, 6] indicated that for the later 2 coatings conductivity was about 5 x 10^7 Siemens/meter or about 84% of pure copper. Since joints and connectors reduce the experimentally measured Q, the conductivity value of coatings may be even closer to pure solid copper. Additional details can be found in references 5 and 6. Computations indicate [7] that 10 μm of copper should be acceptable for even the most extreme future scenarios.

However, low temperature Physical Vapor Deposition (PVD) of copper on stainless steel tubes does not have the same conductivity as copper tubing at cryogenic temperatures. The reason is that straightforward deposition of thick films tends to result in coatings with lattice defects and impurities, which at cryogenic temperature severely degrades conductivity. Even though it is covered in a number of books [8-12] at low temperatures, electrical conductivity is strongly affected by lattice imperfections and by impurities, clear evidence for this is not found is research papers. Understanding of these phenomena is based on the following: in the case of room temperature copper, conductivity is dominated by conduction band electrons, while at cryogenic temperatures, lattice defects and impurities result in large conductivity reduction. Physically, electrons are scattered off lattice defects, small grains and impurities, causing significant conductivity degradation. Straightforward deposition of thick films [13] tends to result in coatings with lattice defects and impurities, since it is well-known that columnar and other microstructures [14] are often observed in conventional, low temperature physical vapor deposition of thick films.

RECENT PVD RESULTS

Before embarking on experimenting with the 50 cm-long cathode magnetron a 15 cm-long copper cathode IAD magnetron, without the extractor, was installed on the old mole, which used to house the magnetron with the 50 cm-long cathode. Due to the differences in geometry the "optimized" Paschen curve discharge conditions, arcing to non-

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copper components occurred during discharge initiation to a point where copper coating adhesion was poor. The cause was that some aluminum was sputtered onto the stainless-steel tube substrate during discharge cleaning resulting in poor adhesion (it was verified after removing the copper coating. After this problem was fixed, good copper coating with good adhesion was obtained. But, these copper coated stainless-steel RHIC tubing sections conductivity measurements in the BNL cryogenic resonator (described in a paper in these proceedings), resulted in conductivity enhancement at 4K of the RHIC tube coated with 10 μm thick copper coating of only a factor of 1.2 of its conductivity at room temperature. This poor result suggested that there could be impurities in addition to lattice imperfections.

Next all magnetron non-copper components, which could be exposed to the plasma, were replaced by copper components, or copper shields were installed. Following this modification, stainless-steel RHIC tubing samples were coated with 5 μm and 10 μm thick copper coating. Conductivity enhancement at 4K of these RHIC tubes coated with both 10 μm and 5 μm thick copper coating was enhanced by a factor of 2.3 of its conductivity at room temperature; i.e. conductivity of $2.3 \times 5.7 \times 10^7$ Siemens/meter, which is within a factor of 2 of what is needed for eRHIC! It could be even higher, since most likely there is contribution to resistivity from connectors, based on the fact that a pure copper tube did not show the expected enhancement. The significance is that 5 μm thick copper coating performed as well is that RHIC coating time can be reduced.

Finally, a “bad” copper coated tube with 2 μm thick copper coating, which was done before all contaminates were removed, with adhesion of 5kg/cm^2 = 4.905×10^4 Newton/m^2 compared to good adhesion that is over that is over 1.2×10^6 Newton/m^2 a factor of at least 24 worse (based on pull machine test) than those with good adhesion, was thermally cycled 10 times from room to cryogenic temperatures. That copper coating stayed intact!

IAD PROTOTYPE DEVICE

To implement ion assisted deposition in 7.1 cm ID tube or even physical vapor deposition (PVD), which usually is performed at distances (cathode to substrate) of 10’s of cm has been an uneasy task, since cathode to substrate distance is 1.5 cm. Adding an extractor makes a difficult task more challenging. First, the following extractor that featured parallel grids, shown in Figure 1 was designed, after which it was realized that those grids will cast “shadows” during deposition. Thus, resulting in non-uniform deposition.

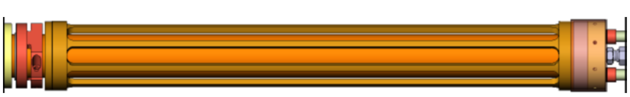

Figure 1: Initial extractor design assembled on the 15-cm copper cathode magnetron.

Therefore, the extractor design was modified. Present, the extractor feature grids that twisted to avoid this problem. Consequently, since the whole extractor has to be made of copper, fabrication became even more complicated. Below are photos of the prototype IAD device and prototype IAD mole. Figure 2 shows the twisted ion extractor installed on the prototype magnetron.

Figure 2: Ion extraction grid assembly, installed on magnetron cathode.

Given previously published estimates of magnetron plasma parameters [4,5,6], the maximum conceivable ion current density, which can be extracted from the magnetron plasma operating at nominal parameters, J_{max} can be estimated from the ion saturation current (basically Bohm sheath criterion), which is $J_{max} = qnc_s$, where q is elementary charge, n plasma density and c_s is the ion sound speed. And, $c_s = (k_B\,[ZT_e + \gamma_i\,T_i]/m_i)^{1/2}$, where γ_i the adiabatic coefficient of ions (of about 3), Z=1 singly charged argon; temperatures T_e is about 1 eV >>T_i. For these parameters, J_{max} is 4464 A/m^2 (almost ½ A/cm^2), which far more than needed for IAD (such a current will damage deposition).

In the figure 2 IAD magnetron, the extractor gap is 1.3 cm (0.013 m). Extracted current can be calculated from the Child-Langmuir law current (CL) (in MKS) is $J_{CL}=4/9\varepsilon_0\,(2e/m_i)^{1/2}V^{3/2}/d^2$, which for argon ions becomes $J_{CL}=8.6\times10^{-9}V^{3/2}/d^2$ A/m^2. Hence, for extraction voltages of 1 KV and 500 V, extracted argon ion current densities are J_{CL}=1.6 A/m^2 and 0.57 A/m^2 respectively, i.e. 160 μA/cm^2 and 57 μA/cm^2 respectively. Grid interception of ions should about 75%. Typical IAD processes [15] utilize ion current densities of 1 – 200 μA/cm^2 with energies of 500 V – 5 KV.

Although the achievable argon ion current density is sufficient for IAD based on the preceding calculations, experiments with grids at various distances (extractor gaps) from the magnetron are to be performed in order to optimize the IAD process in both quality and time.

Figure 3 is a photo of the ion assisted deposition device installed on the carriage of the mole, which previously [4,5,6] successfully utilized for PVD deposition of 10 μm of copper on an assembly of a RHIC cold bore tube, to which the two types of RHIC bellows and additionally sections of RHIC tubing were attached. The magnetron crossed bellows successfully and was able to adjust for changes in wall diameters.

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Figure 3: Photo of ion assisted deposition device. Shown is extraction grid assembly, installed on magnetron cathode. The whole device is installed on the carriage mole.

DISCUSSION

Present status: straight PVD seems to be fairly optimized with coating conductivity being 1.3 x 10^7 Siemens/meter, within a factor of 2 of what is needed for eRHIC. Conductivity enhancement at 4K of the copper coated RHIC tubes was identical both 10 µm and 5 µm thick copper coating. Additionally, a "bad" copper coated tube with 2 µm thick copper coating, which was done before all contaminates were removed, with adhesion of 5kg/cm^2 = 4.905 x 10^4 Newton/m^2 compared to good adhesion that is over that is over 1.2 x 10^6 Newton/m^2 a factor of at least 24 worse (based on pull machine test) than those with good adhesion, was thermally cycled 10 times from room to cryogenic temperatures. That copper coating stayed intact! It's an achieved milestone (with worse-case scenario). At this point ion assisted deposition has not commenced due to effort to fix water-cooled extractor leaks; work in progress.

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