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SURFACE RESISTANCE MEASUREMENT OF Pd COATING FILMS USING CAVITY RESONATOR METHOD

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Abstract

Recently, it was found that palladium (Pd) coating films exhibited ultra-low photon-stimulated desorption and low resistivity values. These advantages suggest that Pd coatings could be applied to small aperture tubes, including undulator vacuum tubes, which have a significant effect on resistive wall (RW) impedance. In previous studies, the DC electrical resistivity of Pd films was measured using the four-probe technique. The surface resistance under high-frequency conditions relevant to accelerators remained insufficiently explored. This study aims to address this gap by employing the "cavity resonator method" to measure the surface resistance of this film under high-frequency electromagnetic fields.

INTRODUCTION

In circular accelerator-based synchrotron light sources, many vacuum components such as beam ducts, absorbers, slits, and photon shutters are continuously exposed to synchrotron radiation (SR) during operation. Photon-stimulated desorption (PSD) from these components is a major source of outgassing and can significantly affect the vacuum environment [1]. Reducing PSD is therefore essential for shortening commissioning time and ensuring stable beam operation. One effective strategy is to apply low-PSD coating materials to the surfaces of these components. The titanium–zirconium–vanadium (TiZrV) alloy is a widely used non-evaporable getter (NEG) material that not only provides vacuum pumping capability but also exhibits lower PSD yields than commonly used structural materials like copper, aluminum, and stainless steel [2].

In previous studies [3,4], Pd/TiZrV films (Pd covered TiZrV) were developed to extend operational lifespan of NEG coatings. TiZrV has high capacity for O_2 and H_2O, so repeated air exposure leads to oxygen saturation, reducing its performance over time. Since Pd is resistant to oxidation and has the ability to adsorb gases like H_2 and CO, the addition of a Pd layer serves to protect the underlying TiZrV and maintain its pumping performance. Pd/TiZrV films also decreased the PSD yields compared to the TiZrV films, indicating the potential of Pd as low-PSD material.

In addition, Pd offers a low bulk resistivity of 10.9 $\mu\Omega\cdot$cm [5], which is significantly lower than that of Ti, Zr, or V. Electrical conductivity is an important factor for accelerator beam tubes, as the finite conductivity of the chamber wall leads to RW impedance, which can cause beam instabilities and RF heating [6]. Thus, low resistivity coatings are desirable, particularly for ultra-low emittance storage rings where RW impedance must be minimized.

In previous work [7], the DC resistivity of Pd films was measured using the four-probe technique. However, the performance of these films under high-frequency conditions, which are more relevant to accelerator applications, has not yet been fully characterized. In the present study, the "cavity resonator method" was introduced to evaluate the resistance of Pd films under RF-frequency electromagnetic fields.

EXPERIMENTAL

Experiment

Surface resistance measurement To estimate the electrical conductivity (σ) of the sample surfaces, the quality factor (Q factor) was measured using the cavity resonator method [8]. Unlike DC-based resistivity measurements, the current induced under high-frequency resonance flows only through the topmost surface of the cavity wall, with its penetration depth determined by the "skin depth". In that case, surface roughness plays a much more significant role, making the measurement more accurately reflect the actual performance of materials in accelerators.

Figure 1(a) illustrates the experimental setup for the cavity resonator method. An inner-polished copper–chromium (CuCr) alloy bucket was enclosed by two end caps to form a closed cylindrical cavity, as shown in Fig. 1(b). The assembled cavity was connected via two signal cables to a network analyzer (N9917A, Keysight Technologies, Inc.). The TE_{011} mode was selected for Q factor measurement. As depicted in Fig. 1(c), the magnetic field distribution in this mode has components in the radial (r) and axial (z) directions, while the electric field is oriented solely in the azimuthal (φ) direction. As a result, the induced current flows only along the φ direction and does not pass through the contact interface between the end caps and the bucket, thereby improving the accuracy of the Q factor measurement.

In a perfectly cylindrical cavity, the resonant frequencies of the TE_{011} and TM_{111} modes are almost the same. To distinguish between them, a groove structure was introduced on the bottom cap of the cavity. Two cavity sizes were fabricated, featuring internal cylindrical dimensions of φ40 mm and φ60 mm in diameter, with a height of 50 mm for both. The calculated TE_{011} resonant frequencies for these cavities were approximately 9.6437 GHz (φ40) and 6.7846 GHz (φ60), respectively.

First, by measuring scattering parameter S_{21}, the loaded Q factor Q_L is obtained as:

$$Q_L = \frac{f_0}{\Delta f(3dB)} \ , \qquad (1)$$

where f_0 is the resonant frequency, $\Delta f(3dB)$ is the half-power bandwidth of the peak. To obtain the unloaded Q factor Q_0, following equation is considered:

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$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{c1}} + \frac{1}{Q_{c2}} \ , \tag{2}$$

where Q_{c1} and Q_{c2} are the external Q factors of ports 1 and 2, respectively. The coupling coefficient β between the network analyzer and test cavity is defined as:

$$\beta \equiv \frac{Q_0}{Q_c}, Q_0 = \beta Q_c \ . \tag{3}$$

Combining the above two equations yields:

$$Q_0 = Q_L(1 + \beta_1 + \beta_2) \ . \tag{4}$$

In case of under coupling (i.e., $0 \le \beta < 1$):

$$\beta = \frac{1 - |S_{11}|}{1 + |S_{11}|} \ , \tag{5}$$

where parameter S_{11} is the reflection coefficient. After measuring S_{11} of ports 1 and 2, the corresponding β is obtained and Q_0 can be calculated. Here, the effects of temperature on the Q factor are negligible.

An identical experiment was set up in CST studio (CST AG, Bad Nauheimer Str. 19, 64289 Darmstadt, Germany). The conductivity (σ) of the sample surface could be adjusted until the Q_0 of the cavity is the same as the experimental value to obtain the σ value of the sample surface.

In addition, the intrinsic surface resistance R_S of a perfectly smooth metal surface under AC stimulation in the GHz regime can be calculated by a simple formula [9]:

$$R_S = \sqrt{\frac{\pi \mu_0 f}{\sigma}} \ , \tag{6}$$

where μ_0 and f are the vacuum permeability and RF frequency, respectively. It can be observed that in the GHz regime, even if the material's σ remains constant, the R_S still increases with frequency. This is an important consideration in accelerator applications.

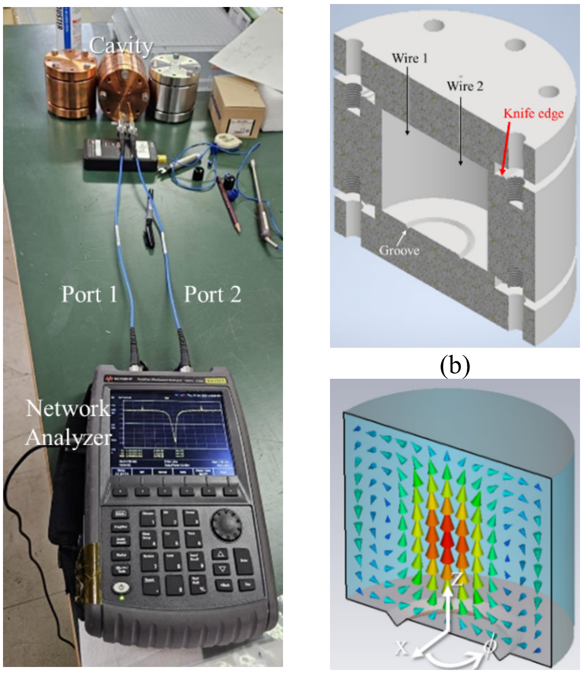
Sample Preparation

As described in the previous section, two CuCr cavities with different inner diameters were fabricated. To ensure accurate Q factor measurements, the inner surface roughness (*Ra*) of each cavity ideally needed to be smaller than the skin depth of CuCr at the resonant frequency, which is approximately 0.7–0.8 μm. Due to material and structural constraints, buff polishing was employed to achieve a near-mirror finish, resulting in a measured *Ra* of approximately 1–2 μm, as measured using the Wide-Area 3D Measurement System (VR-3100, Keyence, Japan).

Because the bucket part of the cavity had to be installed into the magnetron sputtering system for Pd deposition, knife-edge flanges were required. To balance the need for high conductivity in Q factor measurements with the mechanical strength required at the knife edge, CuCr was chosen as a compromise material. As will be shown later, the conductivity of the CuCr used in this study was approximately 80% that of pure copper. The fabricated CuCr cavities were successfully assembled with other stainless-steel components and completed the coating process without any vacuum leaks.

It is important to note that the annular surface on the inner side of the knife edge serves as the contact area with the end caps during Q factor measurements and must be kept clean. Therefore, an aluminum mask was used to protect this area during sputtering.

The coating configuration followed the same design as that reported in Ref. [7], as shown in Fig. 2. During deposition, the cathode voltage was set to 800 V, magnetron field to 200 G, and the Kr pressure to 0.6 Pa. In addition, ribbon-shaped Cu samples with the same curvature radius as the cavities were also installed to verify the film thickness. In this work, the measured Pd coating thicknesses were approximately 8 μm for the φ40 mm cavity and 6 μm for the φ60 mm cavity, both exceeding the theoretical skin depth of Pd (~2 μm). Figure 3 shows photographs of the φ60 mm cavity before and after the Pd deposition. After coating, the Pd film exhibited a mirror-like finish, and its smooth surface contributed to low surface resistance. Besides, the end caps were not coated and remained clean.



(a) (b) (c)

Figure 1: (a) is the setup of cavity resonator method. (b) is the half-section view of the internal mirror polished φ60 CuCr bucket with a "groove". (c) shows the direction of the magnetic field in the TE_{011} mode in the CST simulation.

RESULTS AND DISCUSSIONS

Surface Resistance Results

Table 1 lists the measured Q factors, calculated conductivities, resistances, and surface resistances for each cavity. The conductivity values were derived by comparing the measured Q factors with CST simulations, while the resistance and surface resistance were calculated based on these conductivity values. For reference, the bulk parameters of pure copper and palladium are also included in the table [5].

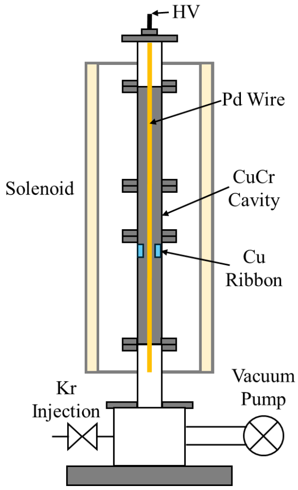
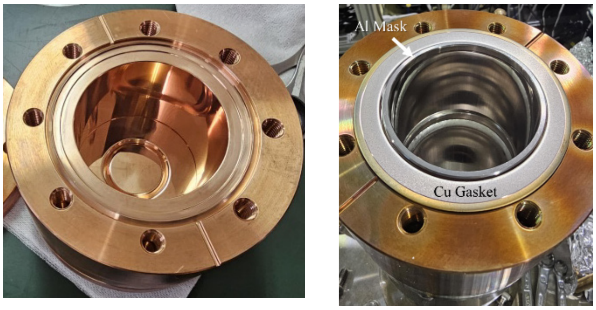


Figure 2: Layout of magnetron sputtering system.



(a) (b)

Figure 3: Photographs of the φ60 mm CuCr cavity (a) before and (b) after Pd film deposition.

Table 1: Q factor, Conductivity, Resistance, and Surface Resistance of each Sample

Sample	Q_0	σ [S/m]	$R = \frac{1}{\sigma}$ [μΩ·cm]	f [GHz]	$R_S = \sqrt{\frac{\pi\mu_0 f}{\sigma}}$ [Ω]
CuCr φ40	25737	4.84E+7	2.07	9.5995	2.80E-2
CuCr φ60	31942	4.76E+7	2.10	6.7832	2.37E-2
Pd film φ40	11175	7.91E+6	12.6	9.5995	6.92E-2
Pd film φ60	15487	8.47E+6	11.8	6.7832	5.62E-2
Cu [5]		5.96E+7	1.68	9.5995 6.7832	φ40: 2.52E-2 φ60: 2.12E-2
Pd [5]		9.26E+06	10.8	9.5995 6.7832	φ40: 6.40E-2 φ60: 5.38E-2

The conductivity of the CuCr cavities was approximately 80% that of pure copper, which falls within the range specified by the material supplier and is sufficiently high to ensure the accuracy of the Pd film conductivity measurements. Furthermore, the measured values were consistent between the two cavities of different radii, indicating good fabrication precision and sufficiently smooth inner surfaces.

As for the Pd-coated cavities, the conductivity of the Pd films was found to be 85% and 91% of the bulk Pd value for the φ40 mm and φ60 mm cavities, respectively, suggesting high film quality and a smooth surface. Given that the φ40 mm cavity operates at a higher frequency with a shallower skin depth, the slightly lower measured conductivity is reasonable—assuming the surface roughness of the Pd coating films is comparable in both cavities.

In a previous study [7], four-probe measurements under similar deposition conditions yielded significantly higher resistivity values (18 μΩ·cm). In contrast, the present study directly evaluated the coated cavity surface, providing a more realistic assessment of the film's electrical performance under conditions relevant to accelerator applications.

CONCLUSION

Dense Pd films were deposited on the surface of CuCr cavities, and their surface resistance was measured under electromagnetic fields at frequencies of about 6.7832 and 9.5995 GHz. The Pd films exhibited over 85% of the bulk Pd conductivity, indicating good crystal quality and a low level of impurities. Overall, the measurement results confirm that the Pd coating offers sufficient conductivity to reduce RW impedance, making it suitable for accelerator vacuum applications.

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