The aim of the present investigation is to determine just how adversely the rf performance of superconductors can be affected by applying thin coatings of similar materials as well as to ascertain whether any beneficial effects on the multipactoring behavior may be realized.

Behavior of Cavities Prior to Application of Coatings

Single cell S-band (2.86 GHz) and X-band (8.6 GHz) cavities of the muffin tin $^2$ variety have been coated. The cavities, fabricated from Nb in two identical halves, are assembled to a Nb spacer ring using In-wire joints. Figure 1 shows one half of an S-band and one half of an X-band cavity. The open nature of the cavity halves offers obvious advantages for the deposition and subsequent visual examination of the coatings.

Fig. 1. Single cell X-band and S-band cavity halves.

At low rf power, and near 1.5 K, measured values for the unloaded quality factor, $Q_0$, of several S-band cavities have been found to lie between $4 \times 10^6$ and $1.5 \times 10^7$. For X-band cavities, $Q_0$'s between $1.2 \times 10^7$ and $2 \times 10^7$ have been regularly obtained. At high rf power S-band cavities that do not suffer premature thermal-magnetic breakdown encounter multipactor barriers between 4-5 MeV/m and between 7-10 MeV/m. (Fields are expressed in terms of $E_{\text{eff}}$, the effective energy gain for electrons. The peak rf magnetic field is 44 Oe/MeV/m and the peak electric field is 1.6 $E_{\text{eff}}$ for single cells). In most cases it is possible to process through the first set of barriers by raising the rf power, but the higher field barriers have only rarely been overcome. While operating in the barrier, the presence of electrons in the cavity has been detected by one (or more) of several methods: discontinuous changes in $Q_0$, abrupt changes in the stored energy, small currents collected by biasing the rf coupling probe, or by X-rays outside the dewar. In the case of cavities fabricated from sheet Nb, heating caused by the impact of electrons has been observed by carbon thermometers placed outside the walls of the cavity near the point of electron impact. An extensive series of tests on 2-cell muffin-tin cavities showed that during multipactoring most of the heating was confined to a single cup wall -- i.e., the bottom of the cup when the cavity is oriented as shown in Figure 1. This wall is in a region of low electric field (high magnetic field) which strongly suggests the presence of spiral orbits bound to the same surface.

The maximum accelerating field obtained in X-band...
cavities has been between 12-16 MeV/m prior to high temperature firing and 16-20.6 MeV/m after firing (at 1900°C). It should be pointed out that the cups of the X-band cavities were fabricated from 0.5 mm sheet Nb. Below 15 MeV/m the breakdown was usually of the thermal-magnetic variety, although occasionally small intermittent electron currents have been detected between 13-15 MeV/m. This electronic activity may be related to the barriers encountered at S-band. Small intermittent electron currents have been detected outside the dewar together with a ~120nA current on the rf probe biased to 67 volts. At this stage it is not clear whether the electron loading observed in this case was due to field emission or to multipactoring.

Coating Methods and RF Results

Three coating materials have so far been investigated by us: Titanium, Titanium Nitride and Rhodium. These materials were deposited primarily by rf sputtering, and in one case by ion-plating. The sputtering was done by the Cornell Dept. of Material Science using an MRC Sputtersphere equipped with a liquid nitrogen trapped diffusion pump and by Millis Research using an AR Varian Sputtering System equipped with a cryopump. (Millis Research also deposited the ion-plated coating). Prior to depositing the film, the coating chamber was pumped down to <5x10⁻⁶ torr, and the surface of the cavities sputter-etched to remove the oxide layer as well as several hundred A of the underlying Nb. During deposition, a small bias was always applied to the substrate to maintain a cleaning action. After deposition the system was bled up to dry nitrogen and the cavities exposed to air for a period of a few days before rf testing. Prior to assembly for rf testing, the cavities were thoroughly rinsed in very pure methanol in order to remove dust particles. The rf performance of the cavities before and after application of the coatings is summarized in Table 1 and in Figure 2.

**TABLE I**

<table>
<thead>
<tr>
<th>Coating/ Thickness/ Frequency/ Band (10⁻⁸ MeV/m)</th>
<th>w/o Plating W/plating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (Å/10⁻⁸)</td>
<td>Freq. (10⁻⁶ MeV/m)</td>
</tr>
<tr>
<td>Ti²⁺/50-100</td>
<td>2A/S 60</td>
</tr>
<tr>
<td>Ti²⁺/190-380</td>
<td>28/S 60</td>
</tr>
<tr>
<td>Ti³⁺/50-100</td>
<td>5A+B/X 10 15⁺</td>
</tr>
<tr>
<td>Ti³⁺/100</td>
<td>3A+B/5 69</td>
</tr>
<tr>
<td>Ti³⁺/200</td>
<td>2A0/X 9 16⁺</td>
</tr>
<tr>
<td>Ti³⁺/320</td>
<td>1A+B/X 16 14⁺</td>
</tr>
<tr>
<td>Rh³⁺/50</td>
<td>3A+B/S 47 7.2⁺</td>
</tr>
<tr>
<td>Rh³⁺/60</td>
<td>1A+B/X 16 14⁺</td>
</tr>
</tbody>
</table>

- Millis Research, b- Cornell Material Science Center

- Multipactoring *-Thermal breakdown

Titanium Coatings. In the first series of tests, titanium was ion-plated onto 2 halves A and B of S-band cavity #2. It should be pointed out that freshly deposited titanium is an excellent gettering agent. Initial attempts to ion-plate Ti in diffusion pumped systems resulted in substantial hydrocarbon contamination as determined by SIMS analysis of preliminary test films. This impurity content was substantially reduced by improved baffles before depositing the Ti films on rf cavities.

Halves A & B were coated in separate runs (due to size limitations of the coating chamber). A glass slide placed adjacent to the sealing surface of half A was coated with 100A (+10%) and the corresponding slide for half B was coated with 380A. On the basis of separate studies of the variation of film thickness with (ion-plating) source to substrate distance it was estimated that the film thickness on the different surfaces of half A varied from 50A at the cup bottom to 100A outside the cup and similarly from 190-380A for half B. As shown in Table 1, there are substantial differences between the performances of the two halves. When halves A & B were tested together (run 150) a net Qo of 1.3 x 10⁻⁶ was measured, and at high power thermal-magnetic breakdown was encountered at 4.9 MeV/m. Unfortunately, the premature breakdown precluded a straight forward determination of the effects of the coating on the multipactoring behavior. However, when half A was tested (run 151) against an unplated Nb half a net Qo of 1.3 x 10⁻⁶ was measured. Assuming, as a lower limit, a Qo of 5 x 10⁻⁷ for the unplated half, the Qo of half A is determined to be > 7.5 x 10⁻⁶. By the same token, the Qo of half B can be inferred to be ~7 x 10⁻⁴. Furthermore, in run 151 the premature breakdown was not encountered and a maximum field of 10 MeV/m could be attained. However, multipactoring is encountered. Curve B of Fig. 2 shows the variation of Qo with increasing field level for run 151. Onset of barriers was observed at 4.6 and 7.9 MeV/m. The behavior is quite similar to that observed prior to plating of the cavity (curve A of Fig. 2) suggesting that the multipactoring characteristics remain unchanged by the plating. However, one cannot eliminate the possibility that multipactoring could be taking place in the unplated half.

![Fig. 2. Behavior of coated and uncoated S-band cavities at high rf power.](image-url)
not clear at the present time. The main purpose served by the parallel X-band coatings is to study the high field behavior in the absence of electron-loading.

**TiN Coatings.** TiN coatings deposited on cavities were prepared by reactive sputtering. At Cornell, Titanium was sputtered in the presence of a N₂ atmosphere with Ti₃N₄ as the sputtering gas. The behavior of TiN films deposited in the presence of N₂ depends strongly upon the N₂ pressure. Titanium will dissolve N in its solid solution up to 20 at. % without any change in its h.c.p. crystal structure. An increase in the N content above this value leads to the formation of the compound TiN, which has a cubic NaCl type crystal structure and is a good conductor. This phase is stable at room temperature, has a wide range of composition from 30 to 53 at. %, and is the only nitrogen-rich phase. TiN prepared by heating titanium in a N₂ atmosphere is a superconductor with Tc depending upon the N₂ and O₂ content. Several investigators have shown that cubic TiN can be formed by reactive evaporation or sputtering at room temperature. However, these authors did not test their films for superconductivity. We prepared several films of TiN (thickness >100Å) both by reactive evaporation and by sputtering. By adjusting the N₂ partial pressure and metal deposition rates, the fraction of Ti atoms to Ti atoms at the substrate was varied from 10 to 1000 for different films. In all cases the films were non-superconducting down to 1.5 K. However, on heating one of these films to 800°C for 2 hours in a vacuum, a superconducting transition temperature of 3.2 K was obtained. On the basis of these results we believe it is unlikely that the TiN films deposited on the cavities are intrinsically superconducting.

Turning to rf results, both X-band cavities A & B and A & B have comparable Q's (4-6×10⁶) and Eₘₜ (6-8 MeV/m). The Q measured for s-band cavity A & B is an order of magnitude higher. Finally, a comparison of curves D and E of Fig. 2, which show the Q vs. Eₘₜ behavior for the S-band cavity prior to and after TiN plating, reveals that the multipactoring behavior of TiN is somewhat more pronounced on applying 100Å of TiN.

Rhodium. 500Å films were sputter deposited by Millis Research on both X-band #1 A&B as well as on S-band #2 A&B. Once again the Q's obtained at S band are substantially higher than those obtained at X-band. An encouraging feature of the high field performance of the S-band cavity is the absence of any multipactoring up to 5.3 MeV/m (see curve E, Fig. 2). After completing the rf test an attempt was made to anodize one S-band half. The complete absence of anodization up to 100 volts confirmed the presence of Rhodium on all surfaces.

**Conclusions.** In evaluating the results of these experiments one must take into account that very thin metallic films have quite different properties from the bulk, or even from thin (500Å) metallic films. For example, it is well known that the surface of titanium is always covered with a natural oxide layer 5 to 70Å thick. It is therefore very likely that a substantial portion of the titanium films on the cavities was converted to the oxide. Similarly it has been shown that oxygen may replace N₂ on the surface of TiN to a depth of a few monolayers. From this point of view only the Rhodium film is relatively free of an oxide layer (less than one monolayer). Another important point is that continuous films are not generally obtained until the thickness starts to exceed 150Å.

Of the 3 materials studied here, Ti has the most pronounced effect on residual losses while TiN has the least. An encouraging feature of these results is that the presence of a normal metal film (perhaps as islands) does not create an overwhelming abundance of "hot spots" so that yields up to 6 MeV/m can still be realized. Unfortunately, the multipactoring behavior is somewhat adversely affected by TiN, and unaltered by Ti. Only the Rh coating appears to have some beneficial effect and this may perhaps be related to the absence of any significant oxide layer. At the present stage this benefit is of little practical consequence since only the soft barrier was suppressed. However, one might be tempted to try a thicker (500Å) TiN coating. In conclusion, the S-band cavity is the absence of any multipactoring up to 25 MeV/m. Furthermore, the "penetration depth" in the normal film will remain considerable to the skin depth so that most of the shielding currents will be carried by the superconducting film.

**Acknowledgements.** It is a great pleasure to acknowledge the important contributions to this work made by Dr. W. Gasko of Millis Research, Mr. B. Addis, and Mr. P. Schuchuck of the Cornell Material Science Center and Dr. J. Roth of the Chemistry Dept. We are also grateful to our colleagues Drs. L. Phillips, R. Sudanlin, and J. Kirchgesner for many valuable discussions during the course of this work.

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