IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

SUPPRESSION OF MULTIPACTORING IN SUPERCONDUCTING CAVITIES*

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Summary

Future application of superconducting cavities to accelerators for high energy physics will probably require cavities designed for the UHF region. Experience has shown that vacuum electronic phenomena, particularly multipactoring, play an important role in limiting performance of cavities in this frequency domain. We report here work aimed at the suppression of multipactoring by deposition of superficial films on superconducting surfaces.

Introduction

Experiments at Siemens laboratories[1] have shown that peak rf magnetic fields in excess of 1400 Oe can be achieved in TM and TE X-band Nb cavities. In typical cavities designed for accelerating high energy particle beams these peak fields would correspond to gradients of the order of 30Mv/m. Attempts to produce these excellent results in superconducting cavities suitable for accelerator application have met with increasing frustration. It is generally recognized that the mechanisms responsible for the limitations in achieving high fields can be broadly classified into two categories. In the first, the limitations are related to the rf magnetic field -- surface defects with depressed critical fields (so called "weak spots") can be driven normal and the excessive power dissipation there may lead to a thermal instability resulting in an eventual "thermal-magnetic breakdown". In the second class of limitations, related to the electric field, vacuum electronic phenomena such as multipactoring and field emission may act as a barrier to prevent further increases in field with rf power. Local heating produced by the impact of electrons may induce transitions to the normal state. [It should be pointed out that electron impact may lead to surface damage creating further weak spots that may later initiate thermal-magnetic breakdown]. Whereas electron loading due to field emission is usually encountered at high fields, (> 10Mv/m) multipactor barriers can occur at relatively low fields.

For a given cavity shape field levels at which multipactor barriers can occur scale with frequency so that for cavities operating in the UHF region multipactoring is likely to be the dominant limiting mechanism. Since one of the future applications of superconducting cavities is most likely to be in the area of storage rings, where the operating frequency is restricted to the UHF band (e.g., 500MHz), it is clear that the multipactoring problem requires solution.

To date two techniques have been commonly used to overcome these barriers in superconducting cavities -- field processing and helium processing. These have had some measure of success, particularly against "weak barriers" -- although barriers once processed through have been known to reappear unpredictably. Multipactoring is also encountered in conventional copper cavities and in high power rf windows. By coating these structures with appropriate materials, e.g., Titanium[2], Titanium Nitride[3], Rhodium[4], etc., multipactoring has been reliably suppressed. This technique has not as yet been applied to superconducting cavities in view of the obvious deleterious effects that such superficial coatings might have on the superconducting properties.

*Work supported by the National Science Foundation.

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 (8.57 Ghz) cavities of the muffin tin[5] 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.

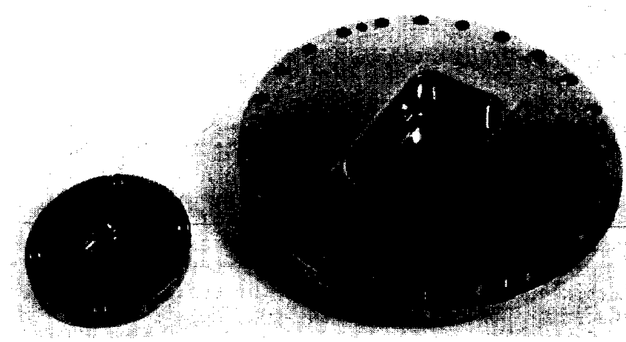

Fig. 1. Single cell X-band and S-band cavity halves.

At low rf power, and near 1.5°K, measured values for the unloaded quality factor, Q_o, of several S-band cavities have been found to lie between 5×10^9 and 1.5×10^{10}. For X-band cavities, Q_o's between $1\text{-}2\times10^9$ 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 7.2-10 MeV/m. (Fields are expressed in terms of E_{eff}, the effective energy gain for electrons. The peak rf magnetic field is 44 Oe/MeV/m and the peak electric field is 1.5 E_{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_o, 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.[5] An extensive series of tests[5] 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 13-16 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 between 4-5 MeV/m. In one fired X-band cavity a field of 20.6 MeV/m was reached when X-rays were 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[6] using an MR 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 < $5\text{x}10^{-7}$torr, and the surface of the cavities sputter-etched to remove the oxide layer as well as several hundred Å 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
Comparison of rf performance before and after plating

Coating/ Thickness (Å±10%)	Cavity/ Freq. Band	w/o Plating Q_0 (10^8)	w/o Plating E_{eff}(max) MeV/m	w/plating Q_0 (10^8)	w/plating E_{eff}(max) MeV/m
Ti[a]/50-100	2A/S	60	8.7†	>7.5	8.7†
Ti[a]/190-380	2B/S	60	8.7†	0.7	4.9*
Ti[b]/150	5A+B/X	10	15*	0.9	8.2*
TiN[a]/100	3A+B/S	69	7.5†	31	4.7†
TiN[a]/200	2A+B/X	9	16*	3.5	8.9*
TiN[b]/320	1A+B/X	16	14*	6.3	6.2*
Rh[a]/50	2A+B/S	47	7.2†	16	7.2†
Rh[a]/50	1A+B/X	16	14*	3.0	8.2*

a- Millis Research, b- Cornell Material Science Center
†-Multipactoring *-Thermal breakdown

Titanium Coatings. In the first series of tests, titanium was ionplated 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 100Å (±10%) and the corresponding slide for half B was coated with 380Å. 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 50Å at the cup bottom to 100Å outside the cup and similarly from 190-380Å 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 Q_0 of 1.3×10^8 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 Q_0 of $1.3\text{x}10^9$ was measured. Assuming, as a lower limit, a Q_0 of $5\text{x}10^9$ for the unplated half, the Q_0 of half A is determined to be > $7.5\text{x}10^8$. By the same token, the Q_0 of half B can be inferred to be ∿ $7\text{x}10^7$. 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 Q_0 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.

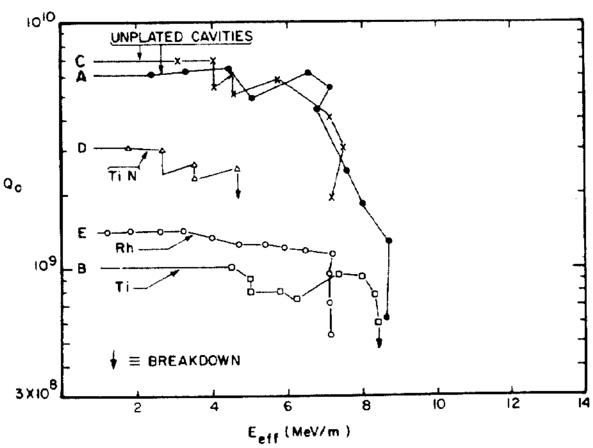

Fig. 2. Behavior of coated and uncoated S-band cavities at high rf. power.

X-band cavities 5A & B were sputter coated with Titanium at Cornell. The purity of Ti films from this system was determined by SIMS analyses, to be marginally better than the ion-plated film from Millis Research. The sputtering time was chosen to yield a 150Å film and the deposition rate was calibrated by measuring the thickness of a test film sputtered for a longer time under identical conditions. For sputtering, the non-uniformity problems are less severe than for ion-plating since a large target (6-8") is placed quite close (1-2") to the substrate. The results show that Q_0 values obtained (∿10^8) are comparable to those measured for S-band cavities, although a more detailed comparison of Q_0 values between S and X band must take into account the frequency dependence of the increased residual losses due to the coating. How to do this is 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 N_2 partial pressure of 4 μ (total pressure = 8μ) and at Millis Research N_2 ∿ (10μ) alone was used as the sputtering gas. The behavior of titanium films deposited in the presence of N_2 depends very strongly upon the N_2 partial pressure. Titanium will dissolve N in solid solution[7] 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, Na-Cl 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 N_2 atmosphere is a superconductor with T_c varying from 1.7 to 5.8°K depending upon N_2 and O_2 content.[8] Several investigators[9] 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 > 1000Å) both by reactive evaporation and by sputtering. By adjusting the N_2 partial pressure and metal deposition rates, the ratio of arrival rates of N_2 molecules 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 #1 A & B and 2 A & B have comparable Q_o's (4-6x10^8) and E_{eff} (6-8 MeV/m). The Q_o measured for S-band cavity #3 A & B is an order of magnitude higher. Finally, a comparison of curves C and D of Fig. 2, which show the Q_o vs. E_{eff} behavior for the S-band cavity prior to and after TiN plating, reveals that the multipactoring behavior is somewhat more pronounced on applying 100Å of TiN.

Rhodium. 50Å 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_o's obtained at S band are substantially higher than at X-band. An encouraging feature of the high field performance of the S-band cavity is the absence of any multipactoring up to 7.3 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 N on the surface of TiN to a depth of a few monolayers[10]. From this point of view only the Rhodium film is relatively free of an oxide layer (less than one monolayer[11]). Another important point is that continuous films are not generally obtained until the thickness starts to exceed 500Å[12].

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 "weak-spots" so that fields up to 8 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) coating of Rh (perhaps even Pt or Au) with a view to obtaining complete coverage of the underlying Nb. It is conceivable that the higher losses in such a thick coating might be lessened by the superconducting proximity effect. For instance, Fisher et.al.[13] have pointed out that a mere 1% increase from zero in the density, ns/n, of superconducting electrons due to pair leakage into the normal film will lower the microwave surface resistance by a factor of 25. Furthermore, the "penetration depth" in the normal film will remain comparable to the skin depth so that most of the shielding currents will be carried by the superconductor below.

Our results show that metallic layers of ∿ 100Å thick do not drastically alter the microwave properties of cavities. Tentatively we have shown that layers of this thickness do not markedly alter vacuum electronic phenomena affecting ultimate breakdown levels. Future work will be directed at trying thicker coatings and to investigating whether perhaps ultimately it is the superficial absorbed gas layer that determines the vacuum electronic behavior of the cavities.

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. R. Shewchuck of the Cornell Material Science Center and Dr. J. Roth of the Chemistry Dept. SIMS facility. We are also grateful to our colleagues Drs. L. Phillips. R. Sundelin, and J. Kirchgessner for many valuable discussions during the course of this work.

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