THE PENETRABILITY OF A THIN METALLIC FILM INSIDE THE RF FIELD*

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Abstract

Thin metallic film was widely applied in various areas. Especially, recently we are planning to apply it in a "Secondary emission enhanced photo-injector", in which a diamond cathode is coated with a metallic film on its back to serve as a current path. The thickness of the film is originally considered to be in the order of 10 nm, which is much less than the skin depth, by a factor of almost 200. One would think intuitively that the RF filed would penetrate such a thin film. However, we found it is not true. The film will block most of the field. This paper addresses theoretical analysis as well as the experimental results, and demonstrates that the penetrability of a thin film is very poor. Consequently, most of the RF current will flow on the thin film causing a serious heating problem.

INTRODUCTION

Thin metallic film, in the order of nanometer, coated on a dielectric substrate has been widely applied in both military and civil engineering. Recently, an idea of Secondary emission enhanced photo-injector was proposed in BNL [1]. Fig.1 shows the schematic.

The laser beam hitting the photo cathode produces photo electrons, which bombard the diamond and produce electron emission coefficient of the diamond. In order to replenish the electrons lost in the diamond, its back must be coated with a thin layer of metal.

The metallic film was considered to be about 10 nm and is transparent to the laser. Since the thickness is much less than the skin depth of the RF which is about 2 micron, it was expected to be transparent for the RF field too, and the RF field of the cavity can serve as an accelerating field for the primary electrons.

If this assumption is not valid, the primary electrons need to be accelerated independently. Moreover, if the film blocks all RF field, the RF current of the cavity will flow on the thin film, that may easily be burnt due to its extremely small volume as well as the thermal capability.

Besides, the conductivity of a metallic film is not proportional to its thickness, but decreases faster due to edge effect [2, 3]. This causes the heating problem even more serious.

This paper addresses the penetrability of the thin metallic film. The experimental results are also presented.

THE PENETRABILITY OF THIN FILM

As shown in the Fig.1, the thin metallic film separates the cavity and the cathode chamber. The cavity is working at strong electric field. The issue is how much field is
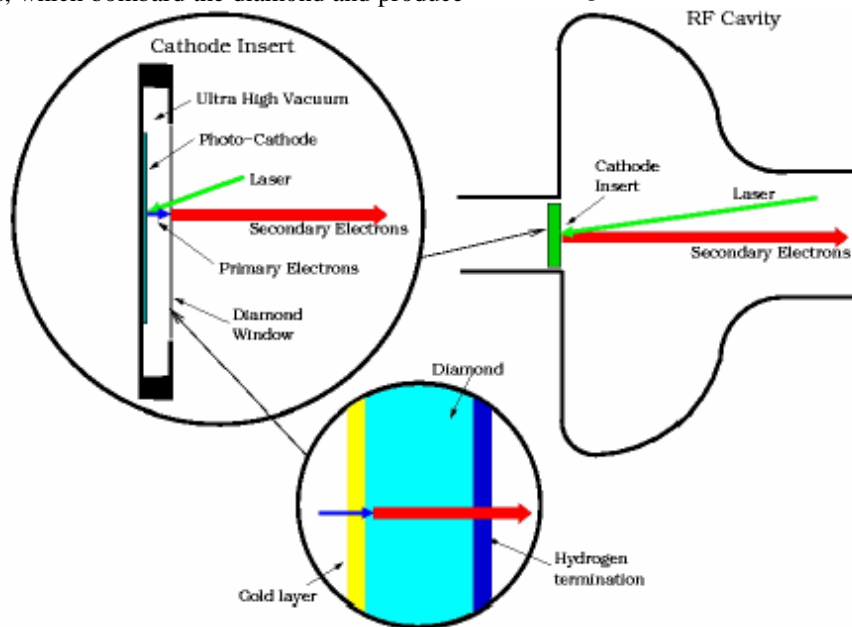

Figure 1: The schematic of the secondary emission enhanced photo-injector.

secondary electrons. The later may be 100 times more than the primary electrons due to the very high secondary

behind the film?

The solution of RF field is usually obtained by virtue of a simulation code. Unfortunately, existing codes do not

deal with a thin resistive film. The film is so thin, it requires too small net lattice to be realistic.

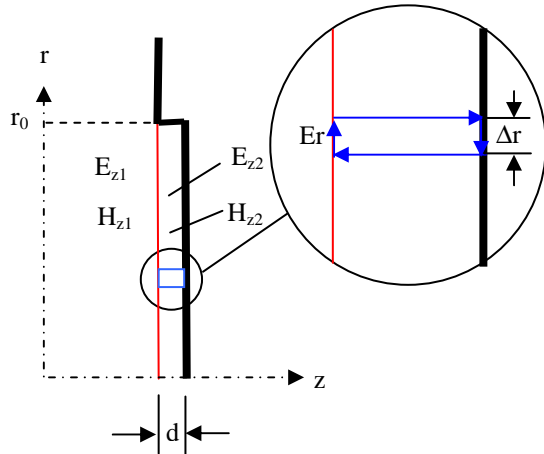A strict analytic solution is also very difficult. In order

Figure 2: The schematic diagram for field analysis.

to address the issue, we apply an approximate analysis to estimate the effect.

Fig.2 shows the schematic. A resistive film with radius of r_0, the red line in the figure, is between cavity and cathode chamber. Its left side is a part of the cavity. The thick black line on the right side is the photo cathode.

Assume the cathode chamber is only a perturbation to the cavity. The field on the left side remains unchanged. For TM010 mode, the fields are:

$$E_{z1} = E_0 J_0(kr)$$

$$H_{\phi1} = j \frac{E_0}{Z} J_1(kr)$$

Assume the electric field behind the film is

$$E_{z2} = \alpha E_{z1}$$

Here α denotes the penetration coefficient. It can be a complex number and a function of location. At the vicinity of $r = r_0$, where E_z drops to zero, or $\alpha(r_0) = 0$. At the vicinity of the center, one can reasonably assume α is a constant. It turns out the magnetic field has the same relation

$$H_{\phi2} = \alpha H_{\phi1}$$

then $\quad i_r = H_{\phi1} - H_{\phi2} = (1-\alpha)H_{\phi1}$

The last equation indicates that the current on the film is strongly dependent on the penetrability of the film. Should it be transparent, α is close to 1, the current is small. On the other end, α close to 0, the film will carry all the current of the cavity as we've mentioned above.

Integrating along the small loop shown in the right plot of Fig.2, we get

$$\oint E \cdot dl = -j \int_S \omega\mu H_{\phi2} ds$$

$$\frac{\partial E_{z2}}{\partial r} + \frac{E_r}{d} = -j\omega\mu H_{\phi2}$$

$$E_r = R_s i_r = (1-\alpha) R_s H_{\phi1}$$

After algebraic manipulation α can be expressed as

$$\alpha = \frac{1}{1 - j \dfrac{2\omega\mu d}{R_s}}$$

where R_s is the surface resistance of the film, and d is the gap as shown in Fig. 2. Obviously, the parameter on the denominator $\gamma = 2\omega\mu d/R_s$ is a criterion of the penetrability. When $\gamma \ll 1$, then $\alpha \to 1$, means transparent. When $\gamma \gg 1$, then $\alpha \to 0$, means opaque. It can be written in another form

$$\gamma = \frac{2\omega\mu d}{R_s} = \left(\frac{4\pi d}{\lambda} \right) \left(\frac{\eta}{R_s} \right)$$

Obviously, the key parameter of penetrability is the surface resistance R_s, not the thickness, even if it is much less than the skin depth. If R_s is much larger than η, the free space impedance, then the film is transparent. On the other hand, if $R_s \ll \eta$, the film will be opaque which is the case of most metallic film. For example, the surface resistance of a 10 nm gold film is 3.4 Ohm at 80 K, and 6.4 Ohm at room temperature. (The edge effect of thin film has been included.) Evidently, it is much less than the free space impedance 377 Ohm.
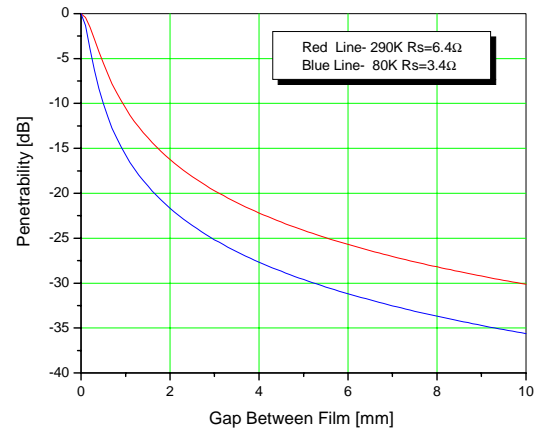

Figure 3: The penetrability vs the gap.

The gap d between the film and the cathode also influences the parameter γ. In an extreme case, when $d = 0$, γ also approaches to 0 and α approaches to 1, meaning completely transparent. It is understandable, because cathode surface is thick enough to be considered as a perfect conductor which is parallel with the resistive film and thus shunt the current on the film. But, when d increases, γ increases rapidly making it opaque.

Let's imagine the case that a thin metallic film directly touch a thick bulk metal, then $d = 0$, so the film is transparent. This explains that the field can penetrate into the metal in a depth of "skin depth", but only if the metal is continuous without air gap.

Fig.3 shows the penetrability of the film as function of the gap between the cathode and metallic film for 10 nm gold at these two temperatures. Fig.3 shows that the field

behind the resistive film will decay 20 dB when gap is 3mm at room temperature, or 1.5 mm at 80 K, the liquid nitrogen temperature.

THE EXPERIMENTAL SETUP

In order to verify the penetrability of the metallic film, an experimental set-up was made as shown in Fig. 4. The copper films of different thicknesses (nominally 50, 100 and 200 Å) were coated on dielectric substrates. The center portion of one substrate was coated with 100 Å thick copper, leaving an uncoated outer ring so that the copper film is not connected to the holder. A blank substrate was used for reference. Since diamond wafer is expensive, we used silicon wafer instead. The wafer is then attached to a metal holder using silver epoxy. The assembled sample is made to contact the cavity wall by pushing a back flange.
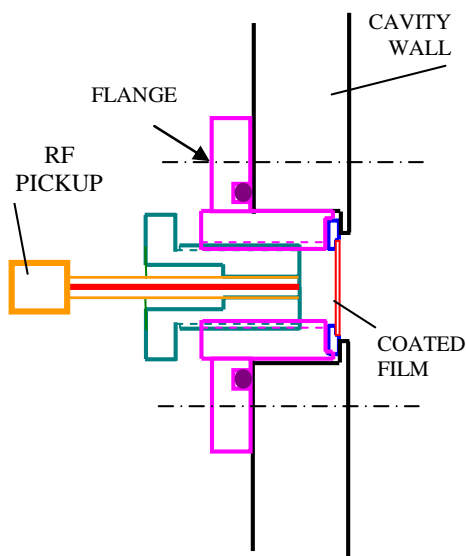

Figure 4: The test set-up.

The cavity is connected to port 1 of the network analyzer. Port 2 is connected to a RF pick-up probe behind the wafer so that one can compare the field strength of different wafers. The pick-up probe is mounted on a screw so that the gap between the film and the probe is adjustable.

THE EXPERIMENTAL RESULTS

The results are shown in Fig. 5. The top cyan line shows the field behind the uncoated blank wafer. The middle red line shows the field of the wafer with 100 Å coating film. The bottom line is of 200 Å coating. It shows that the field decays about 20 dB for 100 Å film and 40 dB for 200 Å film. Evidently, the metallic film really blocks the RF field with only a small percentage field being penetrated.

The blue crosses denote the data of the floating film. It shows the same as the blank wafer. Surely it is expected, because it does not connect to the cavity and no current is on the film. The orange triangles represent the 50 Å film.

It behaves similar to the blank film, though the field should decay about a half of that of 100 Å film. This could be due to the roughness of the substrate which is comparable to 50 Å that could cause the copper film to be discontinuous. An additional wafer of 70 Å coating was made. It shows the decay is about 70% of that of 100 Å coating.

The field decay was observed for uncoated as well as metal coated silicon. Since the wafer is only 10 mm in
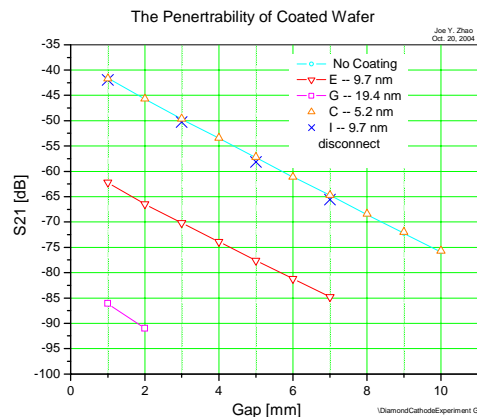

Figure 5: The measured results.

diameter, the space between the metal coating and the cathode can act as a cut-off waveguide in which the field decays exponentially. The measured decay is, hence, a combination of the decay due to the metal film and that due to the waveguide.

Larger wafers were made in order to avoid the cut-off effect. Hopefully further experiments can clarify the remaining problems.

ACKNOWLEDGMENT

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