Fabrication and Testing of L-band Niobium Coated Copper Cavities

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Abstract

L-band niobium coated copper cavities have been developed for the application to TeV linear colliders and FEL drivers. Single cell copper cavities were made by electroforming. Niobium films were deposited by the RF magnetron sputtering method. After the sputtering conditions were optimized, the 1.5GHz single cell coated cavity attained a Q0 of 2.2×10^9 at 1.8K at low fields and a residual resistance of 120nΩ. The 1.3GHz single cell coated cavity has achieved a maximum accelerating field gradient of more than 10MV/m without any field emission or thermal instability.

1. Introduction

Superconducting cavities made of niobium sheets are theoretically expected to attain a maximum accelerating field gradient of 60MV/m. It is however limited to 20~30MV/m by thermal breakdown induced either by electron loading or by enhanced RF losses due to surface defects. Replacing niobium with a higher thermal conducting material like copper should considerably improve the stability against thermal breakdown. A superconducting niobium film, one micrometer thick, is sufficient because the Meissner effect limits the RF field penetration in a superconductor to a very thin superficial layer.

The techniques of coating a copper cavity with a niobium film have been studied at CERN since 1980. 352MHz four-cell coated cavities have been successfully installed in LEP [1]. 1.5GHz single cell coated cavities have been

developed at CERN and CE Saclay. Their coated cavities have high Q0-values, 10^{10}, at 1.8K at low fields but encountered rapid decreases of Q0-values at accelerating fields of 6~10 MV/m [2][3].

KEK has been researching and developing L-band niobium coated copper cavities since 1989 in collaboration with Kobe Steel,Ltd. and Nomura Plating Co.,Ltd. We have noticed that poor local adhesion between niobium films and copper cavities could cause insufficient thermal contact and prevent heat due to the RF loss from dissipating. To overcome these difficulties, we have fabricated copper cavities by electroforming, and deposited niobium films to the inner surface by the RF magnetron sputtering method. Electroforming has the advantages of 1) omitting the welding beads from the equator and iris parts of copper cavities, and 2) producing a smooth inner surface without any defects. These could eliminate the poor adhesion in the local regions. Moreover, RF magnetron sputtering could also eliminate the sources of field emission and activate the film surface because inert gas ions in the RF discharge bombard the surface during film growth due to the self-bias of the substrate (copper cavity).

2. Fabrication of cavities

The main steps of the cavity fabrication are as follows:

1) Fabrication of an aluminum core
2) Electroforming of copper
3) Dissolution of the aluminum core
4) Joining of flanges
5) Electropolishing
6) Coating of niobium film

Spinning and hydroforming shaped the aluminum core from the annealed aluminum alloy pipe. The numerically controlled lathe machined the outer surface, which was then polished mechanically in a roughness of below 0.3μmRz. Electrodeposition of copper (for one week) formed a 3mm copper layer on the aluminum core. After the chemical dissolution of the aluminum core, electropolishing removed the inner surface (about 30μm thick) of the electroformed copper cavity. Electron beam welding joined stainless steel flanges (conflat flanges with a diameter of 152mm) to cut-off tubes of the electroformed copper cavity. There was no vacuum leak in superfluid helium after several thermal cycles. The sample tests of electroforming showed that

the aluminum plates having a roughness of 0.2μmRz brought about a roughness of 0.8~1.0μmRz on the electroformed copper surface after dissolving the aluminum plates, and subsequently, electropolishing produced a roughness of 0.3~0.4μmRz. Auger electron spectroscopies (AES) proved that removing a 5μm electroformed copper surface by electropolishing completely removed impurities, Al, Zn and B, which remained on the electroformed copper surface after the dissolution of the aluminum plates.

2. Coating of niobium films

Sputtering equipment

Figure 1 shows the schematic view of the RF magnetron sputtering system. The gate valve separates the vacuum chambers into the sputtering chamber and the load-lock chamber. The pumping system, which consists of the turbomolecular pump and the cryopump, can achieve a pressure of 3×10^{-6}Pa in the sputtering chamber after baking at 150°C for 24 hours. A pure argon gas (>99.9999%) is used during sputtering. The permanent magnets are placed inside a cylindrical cathode surrounded by niobium pipe (RRR~100) which is cooled by water. These produce a magnetic field of about 200 gauss near the surface of the niobium cathode, increasing the deposition rate considerably. The RF generator (13.56MHz) supplied the power for sputtering.

Adhesion of niobium films

Niobium films deposited on several 1.5GHz half cell copper cavities (OFHC) did not peel off after 10 thermal cycles between the room temperature and the liquid nitrogen temperature. These cavities were kept in dried atmosphere for 90 days. Following this, there was no peeling after 10 thermal cycles. No peeling of the niobium film deposited on the 1.3GHz half cell cooper cavity (OFHC) appeared after it was heated in the vacuum furnace for 4 hours at 600 °C and cooled to room temperature in 48 hours. The ultrasonic vibration in the pure water peeled off the niobium film on the cut-off tubes, but did not cause the niobium films on the equator and the iris to peel.

Thickness of niobium films

Figure 2 shows the thickness of the niobium films deposited on the copper plates (OFHC), which are mounted on a 1.5GHz copper cavity, (a) by the RF magnetron sputtering, (b) by the RF diode sputtering. The RF magnetron

sputtering was carried out for one hour at a power of 1000W at an argon pressure of 2.7Pa. This results in a film thickness of 2μm at the equator, 3~4μm at the iris, and 1~1.2μm at the cut-off tubes. On the other hand, the RF diode sputtering for 2 hours at 1000W at 2.7Pa produces a niobium film thickness of 0.2μm at the equator, 1~1.5μm at the iris, and 1.5~2.0μm at the cut-off tubes.

Quality of niobium films

Figure 3 and 4 show the critical temperature (Tc) and the residual resistance ratio (RRR) of niobium films on the sapphire substrates mounted on the 1.5GHz copper cavity. The niobium films were deposited under the same sputtering conditions as those shown in Fig.2. The RF magnetron sputtering brings about higher critical temperatures, 9.7~9.9 ±0.2K, and residual resistance ratios, 8~20, than the RF diode sputtering because of its higher deposition rates .

Auger electron spectroscopies revealed that each impurity content of O, C and N was below one atomic percent in the niobium films far from their surfaces. Much more impurities, O, C and N, were found at the film surface of about 10nm thick. This could be caused by the adsorption of the residual gases and air after sputtering. 5~7at.% of Cu was detected at the film surface, probably because of a diffusion of the copper substrate.

3. RF performance of cavities

Preparation of cavities

Typical preparation before measuring the RF performance of the coated cavities is as follows:

1) Electropolishing (EP): The horizontal rotating EP machine removes the inner surface (about 30μm thick) of the electroformed copper cavities. They are then rinsed with ultra-pure water. After the coated cavities are tested, the niobium films are dissolved and the copper cavities are electropolished to be coated again.

2) Annealing: The copper cavities are held in the titanium box and annealed for 6 hours at 600~700°C at 10^{-3}~10^{-4}Pa.

3) Coatings: Niobium films of 2~4μm thick are coated by the RF magnetron sputtering for 2 hours at 1500W, 0.4Pa, 300~400°C.

4) Rinsing: The coated cavities are rinsed with ultra-pure water or ethyl alcohol and then mounted on the test equipment in the clean room.

Q0-values at low power

The Q0-values at low power of 1.5GHz single cell coated cavities were measured at Kobe Steel,Ltd. The Q0 at 4.2K were below $4x10^7$ in the initial stage. After the sputtering conditions were optimized, the Q0 at 4.2K was improved to $5.4x10^8$ at 4.2K. The cavity achieved a Q0 of $2.1x10^9$ at 1.8K.

Table 1 shows the Q0 at 4.2K, the Q0 at 1.8K and residual resistance (Rres) of the 1.5GHz single cell coated cavities, F5, F8 and F9. The coated cavity, F5, had a residual resistance of 500nΩ [F5-1]. After the oxidized layer, about 50nm thick, was formed on the surface of the niobium film by anodizing, it was removed by rinsing with hydrofluoric acid (HF). This oxipolish resulted in the decrease of the residual resistance to 120nΩ [F5-2]. The coated cavity, F9, had a residual resistance of 120nΩ without any treatment [F9-1]. This cavity was rinsed with hydrogen peroxide (H_2O_2) to form the oxidized layer (about 3nm thick) on the surface of the niobium film. The residual resistance consequently increased to 270nΩ [F9-2]. The coated cavity, F8, had a residual resistance of 270nΩ [F8-1]. Re-sputtering on this cavity while increasing the deposition rate at the equator from 0.2 to 1.2nm/s decreased it to 130nΩ [F8-2]. This cavity was then annealed for 10 hours at 700°C in a vacuum of 10^{-3}Pa, and rinsed with hydrofluoric acid for a few minutes. As a result, this increased the residual resistance to 320nΩ [F8-3]. The temperature dependence of the surface resistance (Rs) of the coated cavity, F8, are shown in Fig.5.

These results suggest that the high residual resistance is caused by gaseous impurities, such as O, C, N and H, introduced in the niobium film during the film growth and in the superficial oxidized layer on the niobium film after sputtering. The diffusion of Cu and the adsorption of residual gases to the film surface could also increase the residual resistance when the cavity is coated and treated at a high temperature.

Accelerating field gradients

Figure 6 shows the relations between the Q0-values and the accelerating fields of the 1.3GHz single cell coated cavity, which were measured at KEK. The coated cavity achieved the maximum accelerating field gradient of more than 10MV/m without any field emission or thermal instability. The Q0 at 2.1K at low fields was $4.5x10^8$ and the residual resistance was 742nΩ [H3-1]. The unexpected extremely thin film at one side of the cut-off tube, 0.1~0.2μm, due to the unstable discharge during sputtering caused the high residual resistance. After this cavity was coated again under the same conditions, the Q0 at 2.1K at low fields was improved to $1.0x10^9$ and the residual resistance to 237nΩ [H3-

2]. However, the accelerating field was limited at 7MV/m because of the field emission.

Table 1 Q0-values (Q0 at 4.2K, Q0 at 1.8K) and residual resistances (Rres) of 1.5GHz single cell coated cavities.

No.	Q0 at 4.2K	Q0 at 1.8K	Rres(nΩ)	Treatment
F5-1	$2.3x10^8$	$4.8x10^8$	500	as sputtered
F5-2	$3.8x10^8$	$2.2x10^9$	120	oxipolished
F8-1	$2.7x10^8$	$1.0x10^9$	270	as sputtered at 0.2nm/s
F8-2	$5.4x10^8$	$2.1x10^9$	130	re-sputtered at 1.2nm/s
F8-3	$2.4x10^8$	$8.4x10^8$	320	annealed+HF rinsed
F9-1	$4.1x10^8$	$2.2x10^9$	120	as sputtered
F9-2	$3.3x10^8$	$9.9x10^8$	270	H2O2 rinsed

4. Conclusions

The conclusions are summarized as follows:

(1) L-band (1.5GHz, 1.3GHz) single cell copper cavities have been fabricated by electroforming and niobium films have been deposited on them by the RF magnetron sputtering techniques. These have proved to be promising as the fabrication method of the superconducting cavities.

(2) The Q0 of the 1.5GHz single cell coated cavities have reached $2.2x10^9$ at 1.8K at low power. The residual resistances of the coated cavities have been reduced to 120nΩ, but there is still a problem of high residual resistance because of contamination.

(3) The 1.3GHz single cell coated cavity has achieved the maximum accelerating field gradient of more than 10MV/m without any field emission or thermal instability.

References

[1] C.Benvenuti,et al.; Proc.4th Workshop on RF Superconductivity, KEK,Tsukuba,Japan (August 1989) p.869.

[2] C.Benvenuti,et al.; CERN/AT-RF91-6 and Proc.Particle Accelerator Conference,San Francisco,U.S.A.(May 1991),to be published.

[3] D.Bloss,P.Bosland,et al.,in this workshop.

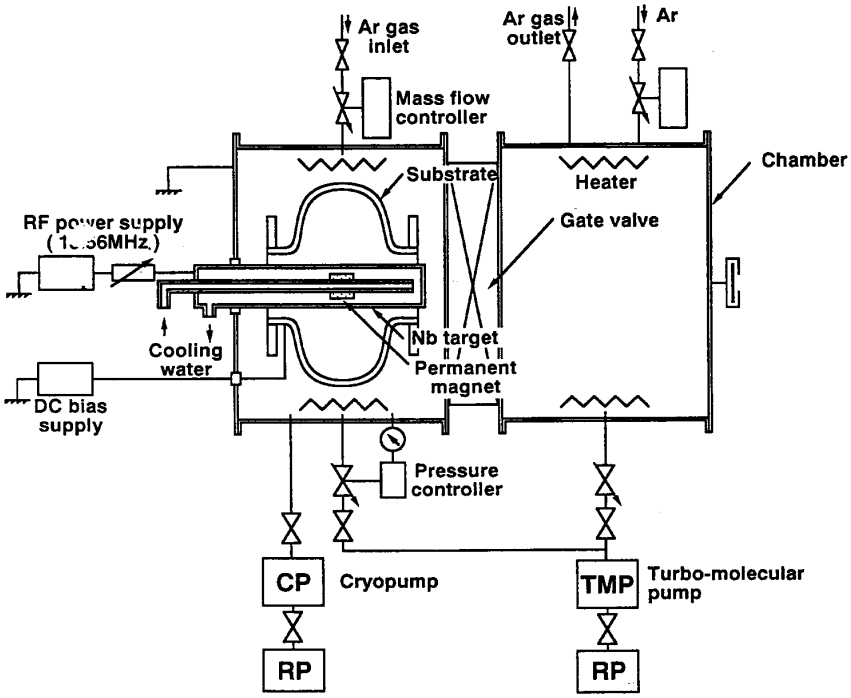

Fig.1 Schematic view of RF magnetron sputtering system.

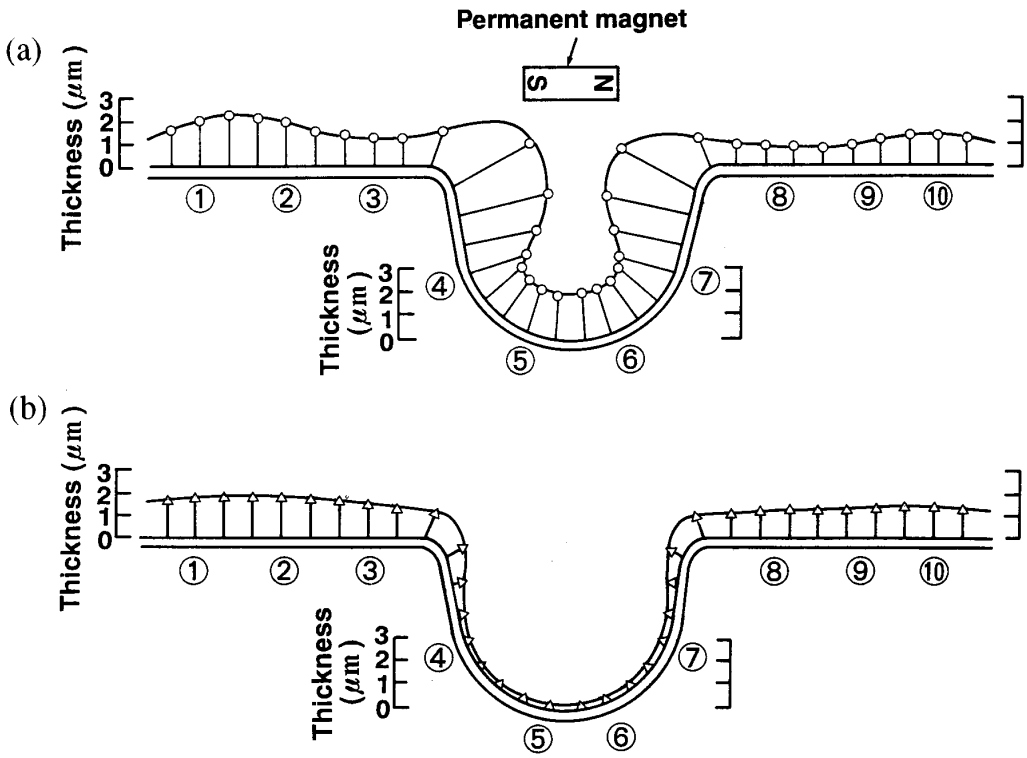

Fig 2 Thickness of niobium films on 1.5GHz single cell copper cavity by (a) RF magnetron sputtering and (b) RF diode sputtering.

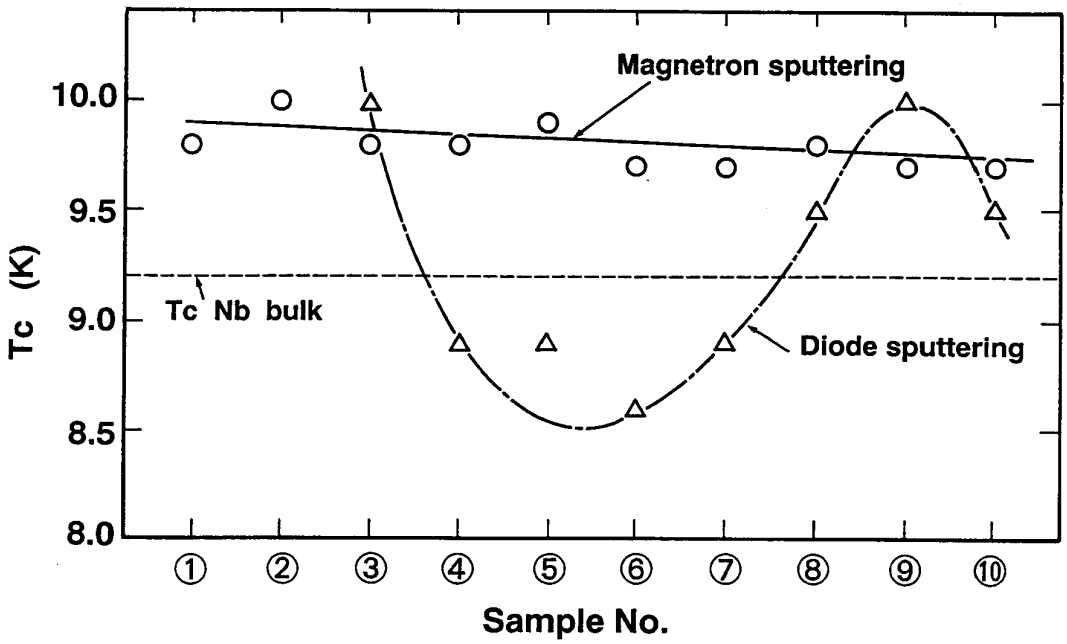

Fig.3 Critical temperature (Tc) of niobium films on sapphire substrates mounted on 1.5GHz single cell cavity.

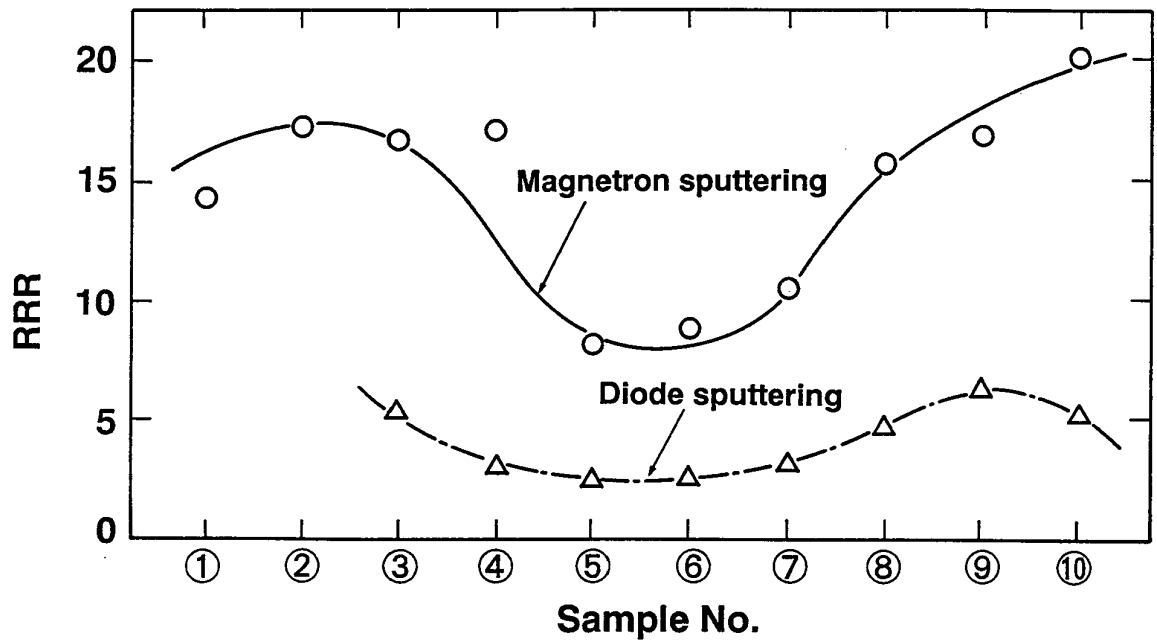

Fig.4 Residual resistance ratio (RRR) of niobium films on sapphire substrates mounted on 1.5GHz single cell cavity.

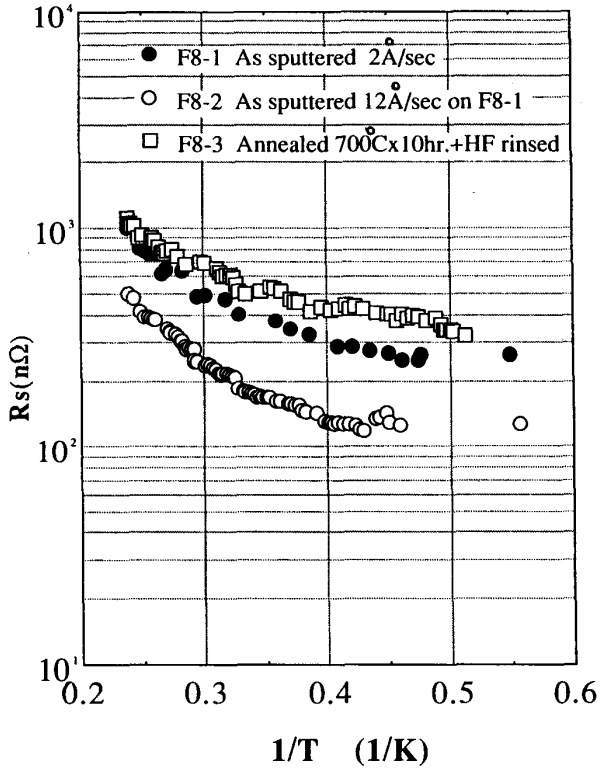

Fig.5 Dependence of surface resistance (Rs) on temperature of 1.5GHz single cell coated cavities.

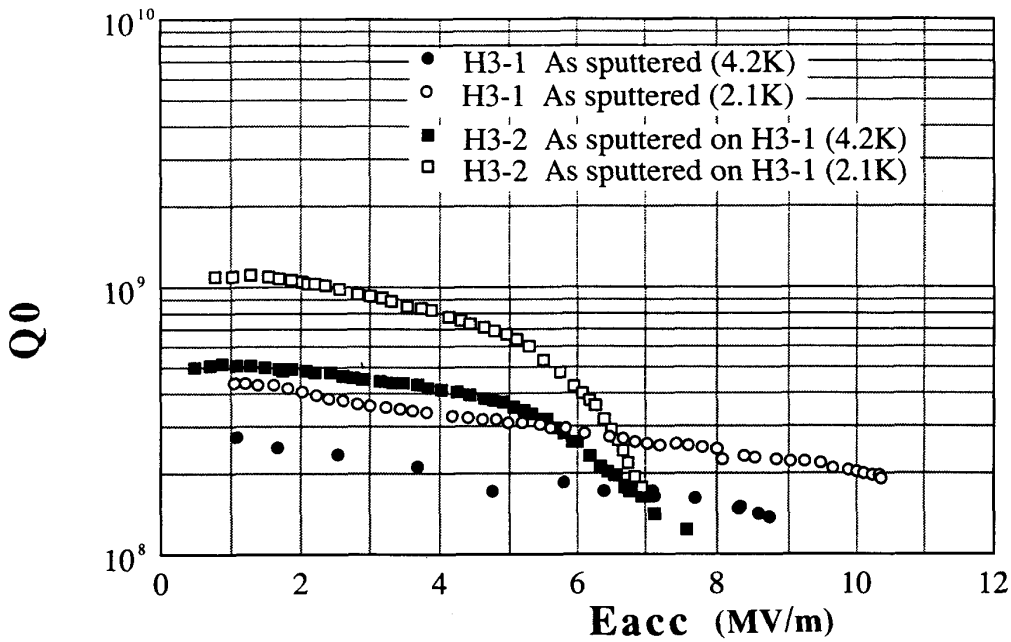

Fig.6 Q0-values vs. accelerating fields (Eacc) of 1.3GHz single cell coated cavities.