MEASUREMENT OF FIELD EMISSION DARK CURRENT FROM THE TITANIUM, COPPER, AND STAINLESS STEEL ELECTRODES UNDER THE HIGH DC-FIELD GRADIENT CONDITION

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Abstract

We have continued a systematic study on the field emission dark current under the high DC-field gradient by using a compact test apparatus at KEK. The dark current have been already measured for the several sample electrodes with same figures but made of different materials of stainless steel (SUS), copper (Cu), and titanium (Ti).

For the SUS, the field gradient of 36 MV/m was achieved with the dark current level of less than 1 nA, and the microscopic field enhancement factor β was estimated to be ~40. For the Cu, it was 47 MV/m with β of 56. These data were taken for the same gap length of 1 mm and the same maximum-field-applied area of ~7 mm^2.

At present, we have been testing the Ti electrode samples. It was expected that Ti should give the higher performance than SUS and Cu due to the lower secondary electron yield and sputtering rate. The preliminary results for the pure-Ti electrode showed the much higher field gradient of 88 MV/m for 1 nA dark current level and β of 30 under the same experimental conditions for SUS and Cu.

1 INTRODUCTION

In order to assure the best performance of high field gradient devices, such as an electron DC-gun, a klystron, an accelerator tube and an RF-cavity, the reduction of field emission dark current from metal surface is very important. The increase of dark current usually brings the pre-breakdown or the worse UHV conditions. In the worst case, it initiates electrical breakdowns, and these damages degrade the device performance.

It is known that the dark current is strongly dependent on metal surface conditions. The existence of microscopic protrusions, metallic particles adhering to the surface or micron size impurities that have the band structure of insulator are considered to enhance the dark current [1]. But there seems still no complete understanding of the relation between the dark current and the metal surface conditions.

Therefore we have tried to make clear it by using a compact DC high voltage test stand at KEK. The dark currents from SUS and Cu electrodes treated by different surface treatment methods have been already measured. From these experiments, it was suggested that the magnitude of dark current is dependent on the fabrication procedures of the electrode and the cleanliness of the crystal structure and material [2, 3].

It was also suggested that the secondary electron yield and ion-sputtering rate have the influence on the enhancement process of dark current. We paid a special attention to Ti as a material of the better electrode, because both of the secondary electron yield and the sputtering rate of Ti are lower than those of SUS and Cu.

The preliminary behaviour of dark current from the pure-Ti electrode was measured recently, and the pure-Ti showed much better performance than SUS and Cu under the same conditions.

In this paper, the results of dark current measurements for SUS, Cu, and Ti are described for comparison.

2 EXPERIMENTAL APPARATUS

Fig. 1 shows the schematic view of the test stand. This test stand was built for basic study of field emission dark current under the high DC-field gradient condition (~100 MV/m) with ultra-high vacuum of 10^{-11} Torr.

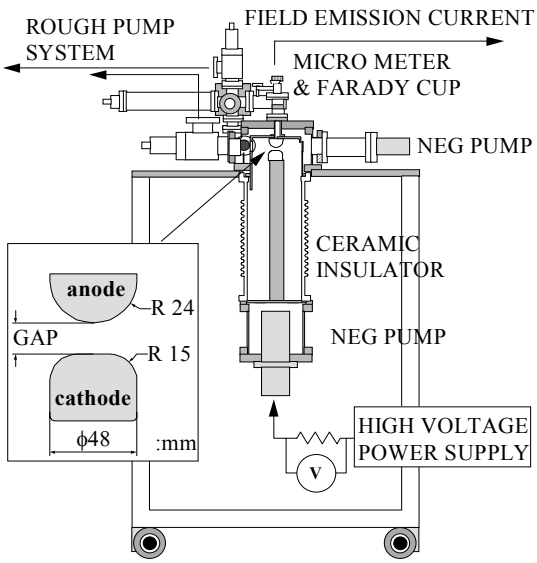

Figure 1: Schematic view of a DC high voltage test stand.

To achieve the ultra high vacuum, the main vacuum chamber of this apparatus was made of a very high quality stainless steel SUS316L called NK-CleanZ, which contains much fewer non-metallic impurities. All vacuum components except the electrodes were finished to a mirror-like surface by electro-chemical buffing (ECB). To avoid any contamination due to the dust, this apparatus was assembled in class-1 clean room just after rinsing with hot-ultra pure water (80 MΩ∗cm, 70 °C). After baking at 250 °C for 1 week, the chamber is pumped down to ~1 x 10^{-11} Torr.

The field gradient can be changed by control both of the gap separation of the electrodes (0.5~20 mm) and of the bias voltage (~100 kV). The maximum-field-applied area with 7 mm^2 at the cathode centre is almost unchanged for the different gap separation length from 0.5 to 3.0 mm, because of the anode shape has a flat top of ϕ 2 mm.

The dark current emitted from the cathode is collected at the anode and measured by a pico-ampere meter.

3 PREPARATION OF ELECTRODES

3.1 Stainless Steel

The SUS electrode was machined from NK-CleanZ. By the electro-chemical buffing, the surface roughness of the electrodes was made less than 0.1 μm without pits on the surface. As the final surface treatment, hot-ultra pure water (80 MΩ∗cm, 70 °C) rinsing was employed in the class-1 clean room. Table 1 shows the specifications of NK-CleanZ and JIS standard SUS316L material.

Table 1: Chemical compositions of SUS316L (%).

	C	Si	Mn	P	S	Ni	Cr	Mo
NK-CleanZ	0.004	0.12	0.27	0.001	0.00006	14.96	16.8	2.36
JIS-SUS 316L	<0.03	<1.0	<2.0	<0.04	<0.03	12~16	16~18	2~3

3.2 Copper

All the samples were machined from a class-1 OFHC (Oxygen Free High Conductivity) copper block that has the purity of 99.996 % and is forged by HIP (Hot Isostatic Pressing) method. The diamond turning method in a clean room with an air filter of 0.3 μm was employed as the final machining to mirror-like finish. After diamond turning, four different types of combination of surface treatment and rinsing method were employed for the test electrodes.

The electrode rinsed with ultra-pure water after diamond turning showed the best results. The results were worsen by the surface treatment of EP (Electro Polishing) and OUR (Ozonized Ultra-pure water Rinsing). For the Cu, we showed only the best results of Cu in this paper. The details of the dark current measurement for Cu electrodes have been already published in the reference [2].

3.3 Titanium

The Ti electrode was machined from JIS grade-2 pure Ti. The mirror-like surface was obtained by buff polishing. The HPR (High Pressure Rinsing, 80 kg/cm^2, 5 minutes) with ultra-pure water was employed as the final surface treatment in the class-100 clean room. Table 2 shows the specifications of JIS grade-2 pure-Ti.

Table 2: Chemical compositions of JIS grade-2 pure-Ti (%).

	C	H	O	N	Fe
JIS grade-2 Pure-Ti	—	0.015	0.20	0.05	0.25

4 RESULTS AND DISCUSSION

4.1 Dark Current Measurement

To avoid any electrical breaks down, the dark current measurement was done very carefully after the long time current conditioning for a few days to 2 weeks. The results of dark current measurement for SUS, Cu, and Ti at the different gap length of 1.0 and 0.5 mm are summarized in Fig. 2, indicated by straight (—) lines and dotted (----) lines, respectively.

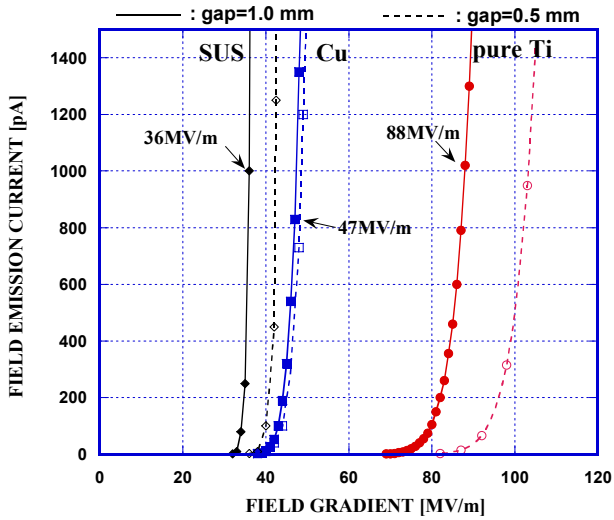

Figure 2: The dark current from SUS, Cu, and Ti.

For the SUS, the dark current was began to appear at the field gradient of 32 MV/m, and rose up to level of 1 nA at 36 MV/m at the gap length of 1.0 mm. For the Cu, the dark current started to appear at 38 MV/m and rose up to nearly the same level of SUS at 47 MV/m. Both of the above data were the best records among similar experiments made by other groups as far as we know.

Moreover, the behaviour of dark current from Ti showed the much better performance than that of SUS and Cu. The dark current kept the level under 1 pA up to the 70 MV/m, and the very high DC-field gradient of 88 MV/m with the dark current level of 1 nA was achieved under the same conditions for the SUS and Cu electrodes.

In Fowler-Nordheim formula, the magnitude of field emission depends on only the field gradient on the metal surface. But experimentally, there are many effects that

enhance the dark currents in addition to the field gradient. One of the mechanisms of such enhanced emission, we considered that ion sputtering and secondary electron yield are important. The effects of these scattering processes can be observed as the gap dependence of the magnitude of dark current, since the bombardments of electrodes by electrons or ions accelerated by the bias voltage may cause the creation of secondary particles either at the anode or cathode. If the gap length becomes wider, the energy of electrons or ions for bombardment becomes larger, and it can enhance the dark current.

In our conditions, the Ti gave the much higher field gradient than Cu, although Ti showed the larger gap dependence than Cu. Therefore it seems to suggest that the lower secondary electron yield and sputtering rate of Ti compared with SUS and Cu, as shown in Table 3 and Table 4, are not the main reason for Ti to show the better performance than SUS and Cu. The main reason is expected that the original field emissions are much smaller than Cu and SUS, since the dark current wasn't observed for Ti up to 70 MV/m with the gap length of 1.0 mm. Further studies to understand the field emission mechanisms for Ti are obviously required.

It must be remarked that the lower secondary electron yield and sputtering rate of Ti are expected to be more effective to suppress the high-voltage breakdowns in comparison with SUS and Cu.

Table 3: Coefficient of secondary electron yield.

	Ti	Cu	Fe	Ni
Secondary electron yield	0.9 @280eV	1.3 @600eV	1.3 @400eV	1.3 @550eV

Table 4: Atomic radiation rate against the incident Argon ion.

	Ti	Cu	SUS
Sputtering rate (atoms/ion)	0.58	2.3	1.3~1.4

4.2 Microscopic Field Enhancement Factor

The characteristic of field emissions from metal surface under high DC-field gradient is also expressed using the microscopic field enhancement factor β. It is obtained by fitting the data points of Fowler-Nordheim (FN) plot[1] by a straight line. Fig. 3 showed the summary of the FN-plots of our experimental results for SUS, Cu, and Ti at the different gap length of 1.0 and 0.5 mm with the same way of Fig. 2. The β-values of 40 for SUS and 56 for Cu had been already obtained at the gap length of 1.0 mm. In this experiment for the Ti, the β-value of 30 was obtained under the same conditions for SUS and Cu electrodes.

The gap dependence of β was also observed, but it was rather small. All of these β-values were very small compared with those of the realized DC high voltage devices. Our results suggest that the well-refined fabrication procedures for each material made it possible to increase the field gradient keeping the lowest level of dark current.

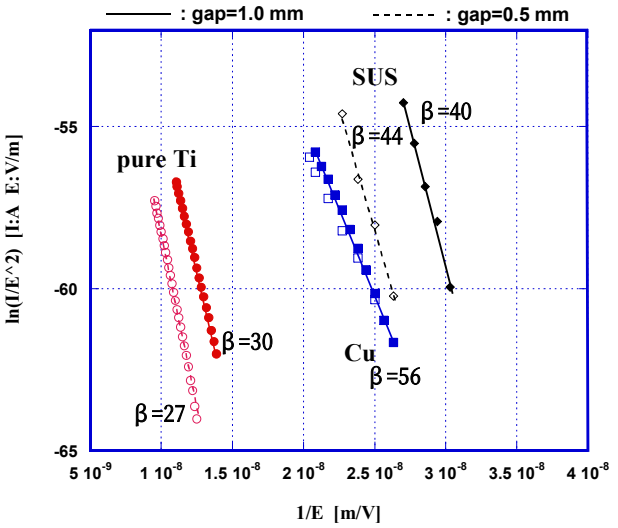

Figure 3: Fowler-Nordheim plot of the each electrode.

5 CONCLUSIONS

In our experiment for pure-Ti electrode, the high DC-field gradient of 88 MV/m at the gap length of 1.0 mm was achieved with dark current level of 1 nA. The microscopic field enhancement factor β was estimated to be 30 for this surface. The dark current from the Ti-alloy have been also measured at TJNAF, also the experimental conditions are different [5]. Our data shows clearly that the Ti electrode has an excellent property to suppress the field emission dark current under the very high DC-field gradient around 100 MV/m.

It was also suggested that the low secondary electron yield and sputtering rate is not main reason of small dark current, also they should be effective to suppress the high voltage breakdowns. The appropriate new materials and new fabrication procedures should gave the better performance of field emissions as like as the Ti.

As further experiments, the tests of Mo and other metal electrodes are scheduled and these investigations will be helpful to understand the common and different mechanisms of field emission from the metals.

6 REFERENCES

[1] R.V.Latham, High Voltage Vacuum Insulation: BASIC CONCEPTS AND TECHNOLOGICAL PRACTICE, Academic Press London, 1995 Chap.3

[2] C.Suzuki et al, Nucl. Instr. and Meth. A 462 (2001) 337

[3] H.Matsumoto, Proceedings of International Linac Conference 96 (LC96), Geneva, 1996, p.626

[4] R.V.Latham, High Voltage Vacuum Insulation: The Physical Basis, Academic Press London, 1981, Chap.2

[5] C.K.Sinclair et al, Presented at PAC 2001, Chicago, IL, June 18-22, 2001

[1] FN plot is two-dimensional plot of I/E^2 versus 1/E, using the data of the dark current (I) and the field gradient (E), and the β-value for the ideal metal surface is equal to 1.0 [4].