# AN ELECTRODE WITH MOLYBDENUM-CATHODE AND TITANIUM-ANODE TO MINIMIZE FIELD EMISSION DARK CURRENTS

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*Abstract*

A series of dark current measurements are performed for Molybdenum (Mo) and Titanium (Ti) electrodes, and the results are analyzed to separate the primary field emission current from the total observed dark current. The analysis shows that Mo exhibits very low primary field emission current as a cathode, and Ti also exhibits a lower enhancement effect of dark current due to electron and ion bombardments of cathode and anode. An electrode configuration with Mo cathode and Ti anode is thus examined, and it is confirmed that a field gradient of as high as 130 MV/m for 1 nA total dark current is possible for an electrode gap of 0.5 mm and an effective cathode area of 7 mm$^2$.

## INTRODUCTION

The initial phase of dark current or pre-breakdown phenomenon, dominated by primary field emission is usually weak, and does not cause fatal damage in high-voltage devices. More serious breakdown phenomena that degrade device performance are triggered by the same field emissions but are enhanced by an additional positive feedback mechanism. However, for photoemission source using GaAs-type photo-cathodes with a negative electron affinity (NEA) surface to extract electrons into vacuum, even a weak pre-breakdown current significantly reduces the cathode lifetime [1]. The NEA surface realized by a surface dipole layer of Ga(−)–Cs(+) is delicate and easily destroyed by small disturbances induced by dark current. Thus, technology for reducing pre-breakdown dark current is essential for the photoemission devices using an NEA-GaAs surface. Polarized electron source (for linear collider) and low-emittance electron source (for ERL) are representatives of such devices.

The dark current properties of SUS and Cu surfaces have already been investigated using a compact test stand constructed at KEK. Based on these experiments, it has been suggested that the magnitude of dark current is dependent on both the electrode fabrication process and the purity of the crystal structure of the material [2]. Thus, using the same apparatus, our group undertook a systematic study of the dark current from Ti and Mo electrodes. This paper presents the results of these experiments, and introduces a new analysis method for separating primary field emission current from total dark current based on experimental data for the gap-separation dependence.

## APPARATUS AND ELECTRODE

The test stand was built for basic study of field emission dark current under the high DC-field gradient condition (~200 MV/m) with ultra-high vacuum of $<10^{-11}$ Torr. In order to obtain a high-quality UHV, the main vacuum chamber was fabricated using re-melted stainless steel (NK-Clean-Z), which contains much less non-metallic impurities than SUS316L. The applied field gradient could be changed by controlling the gap separation of the electrodes (0–20 mm) and the bias voltage (0–100 kV), allowing the dark current under a given field gradient to be measured with respect to different gap separations. The Ti electrode was machined from JIS grade-2 pure Ti, and a mirror-like surface was obtained by buff-polishing. The Mo electrode was machined from a single-crystal Mo block (purity: 99.999%), and a mirror-like surface was prepared by diamond paste polishing. The specimens were finally treated by high-pressure rinsing (80 kg/cm$^2$, 5 min) with ultra-pure water in the class-100 clean room.

## DARK CURRENT MEASUREMENT

To avoid trivial electrical breakdown, the dark current measurements were done very carefully using the long time current conditioning for a few days to 2 weeks. The results of dark current measurements are shown in Fig. 1, where the dark current is plotted as a function of applied field gradient at the cathode surface. The Ti and Mo electrodes exhibited no dark current up to 80 and 83 MV/m, reaching 1 nA at 103 and 115 MV/m at a gap separation of 0.5 mm, respectively. This represents much higher performance than either SUS or Cu.

The dependence of dark current on gap separation is also shown in Fig. 1. For Ti, it exhibits a dark current of ~1 pA with a 0.5 mm gap and > 100 pA with a 1.0 mm gap under the same field gradient of 80 MV/m. A stronger dependence is observed for Mo. It has a dark current of less than 1 pA for 0.5 mm gap separation, but a dark current of over 1 nA for 1.0 mm gap separation under a field gradient of 83 MV/m.

Fowler-Nordheim theory provides a fundamental viewpoint for field emission phenomena, but it is unable to predict the dependence of dark current on gap separation [3]. The current enhancement effect due to bombardment of the anode and cathode by electrons and positive ions is expected to stimulate additional dark current. Under a given field gradient applied to the cathode surface, a wider gap results in higher kinetic energies of electrons and positive ions, and thus the enhancement effect is expected to become more significant. Table 1 lists experimental values of secondary electron yield for specific energies of incident electrons and sputtering rates under 600 eV Ar+ ion bombardment. Both rates are larger for Mo compared to Ti, and it seems quite reasonable that a larger enhancement effect and thus larger gap separation dependence is observed for the Mo electrode.

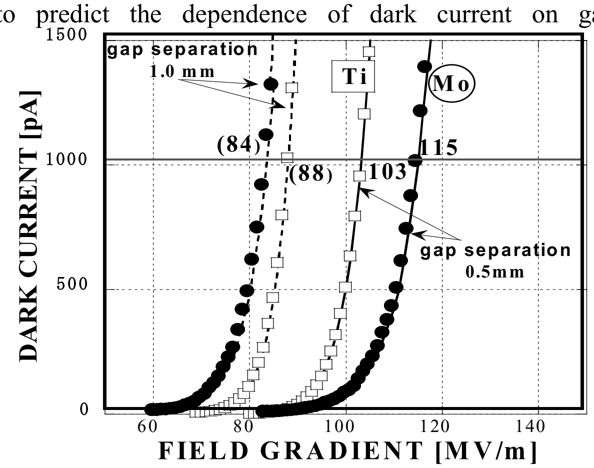


Figure 1: Dark currents from Ti (□) and Mo (●). Gap separations are 0.5 mm (—) and 1.0 mm (----).

Table 1: Secondary electron yield for normal-incidence electrons and sputtering rate by 600eV $Ar^{+}$

| | Ti | Mo |
|---|---|---|
| **Secondary electron yield** | 0.9@280eV | 1.25@375eV |
| **Sputtering rate (atoms/ion)** | 0.58 | 0.93 |

## SEPARATION OF PRIMARY FIELD EMISSION CURRENT FROM TOTAL DARK CURRENT

The total dark current will approach the primary field emission current with decreasing gap separation reaching coincidence at zero gap separation, as the enhancement effect must also become smaller and finally disappear. Thus, the primary field emission current under a given field gradient will be equivalent to the total dark current extrapolated to zero gap separation.

The field gradients producing a total dark current of 1 nA are plotted with respect to gap separation for the Mo and Ti electrodes in Fig. 2. The following formula was used to approximate the field gradient of *E(I,d)* [MV/m] giving the total dark current of *I* [A] at the gap separation of *d* [mm]

$$E(I,d) = \frac{E(I,0)}{1+\alpha d}. \quad (1)$$

where $\alpha$ is a constant representing the enhancement effect [$mm^{-1}$], and *E(I,0)* is the intercept of the field gradient at zero gap separation, corresponding to the magnitude of the field gradient giving the field emission current of *I*.

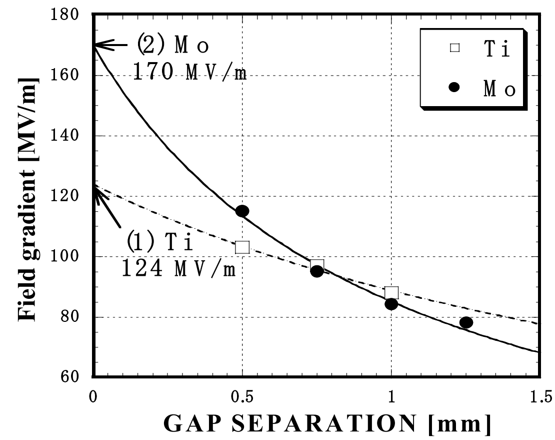


Figure 2: Fitting and extrapolation of data points for (1) Ti and (2) Mo electrodes. The field gradient corresponding to a primary field emission current of 1 nA is obtained as the intercept at zero gap separation.

Using this equation, the data points are fitted with respect to the free parameter $\alpha$, yielding field gradients corresponding to 1 nA primary field emission current of 124 MV/m for Ti and 170 MV/m for Mo. A similar extrapolation was performed for dark currents between 1 pA and 1 nA. The free parameter $\alpha$ was adjusted in each case, but had an average value of 0.4 ± 0.02 for Ti and 1.0 ± 0.04 for Mo. This constancy of $\alpha$ over the entire range of dark current indicates that the gap separation dependence is well approximated by equation (1). Using the extrapolated data for *E(I,0)*, a two-dimensional plot of field emission current vs. field gradient can be

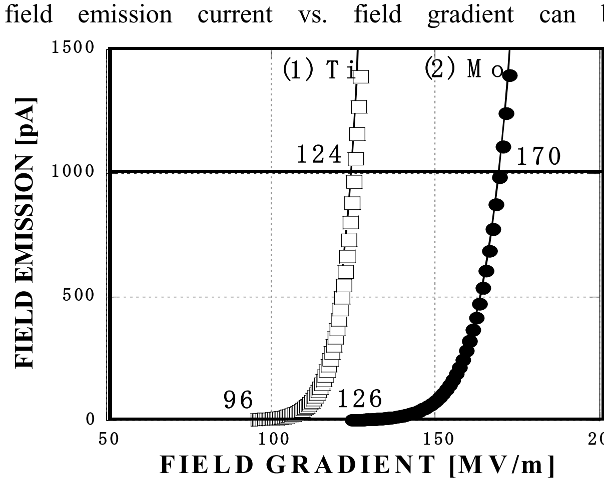


Figure 3: Estimated primary field emission current from (1) Ti and (2) Mo surfaces as a function of field gradient at the cathode surface.

constructed, as shown in Fig. 3.

Comparing the plots for Ti and Mo, it is obvious that the primary field emission from the Mo surface is much smaller than that from the Ti surface, consistent with the original expectation. As the F-N equation indicates that the field emission current is inversely proportion to the work function of the electrode material, the present analysis results seem quite reasonable, where the work functions of Mo and Ti are 4.6 and 4.3 eV, respectively.

## REDUCTION OF DARK CURRENT

The above analysis showed that Mo and Ti have different advantages, that is, Mo exhibits low primary field emission, while the enhancement effect due to bombardment is weak for Ti. Thus, a Mo cathode and Ti anode may represent the best electrode combination.

Dark current measurements were made for such a Mo-Ti electrode configuration at different gap separations. The results for 0.5 mm gap separation are plotted in Fig. 4 in comparison to the results for the Mo-Mo and Ti-Ti configurations. As expected, the Mo-Ti configuration exhibits the best performance with a dark current of only 80 pA at 115 MV/m, increasing to 1 nA at 130 MV/m. The evaluated behaviour of primary field emission currents for the Mo-Ti electrode agrees quite well with that for the Mo-Mo electrode. It supports the validity of the present analysis method.

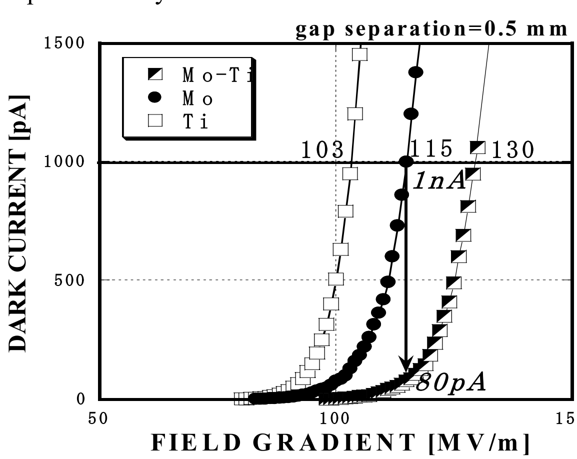


Figure 4: Dark currents for Mo-Ti, Mo-Mo, and Ti-Ti electrodes as a function of field gradient at the cathode surface for a gap separation of 0.5 mm.

## FIELD ENHANCEMENT FACTOR β

Although the field enhancement factor β defined in the F-N equation is independent of gap separation [4], a clear dependence is apparent in the experimental data. Fig. 5 plots β for the Mo-Ti, Mo-Mo and Ti-Ti electrode configurations with respect to gap separation. As a gross feature, the value of β increases linearly with gap separation. It is reasonable since the dark current enhancement effect becomes more significant as the gap becomes wider and is interpreted as an increase in the local field strength in the F-N equation.

The β values for both Mo-Ti and Mo-Mo electrodes at zero gap separation must to be same (β≈23), since the same field emission current is expected for them. The straight lines fitting the gap-dependent β value for Mo-Mo and Mo-Ti electrode in Fig. 5 seem to cross the vertical axis at the same point (β≈23). This agreement in the β values by two different fitting methods demonstrates

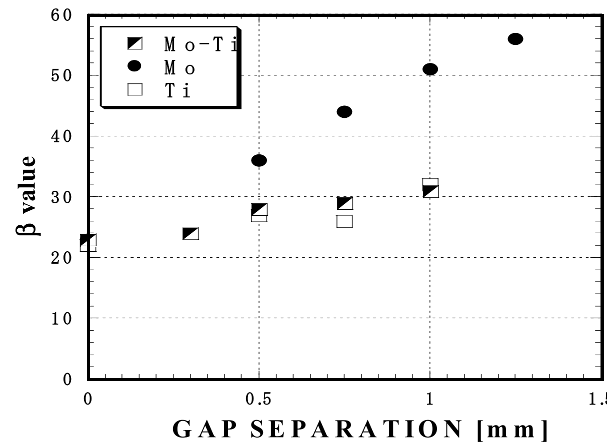


Figure 5: Dependence of enhancement factor *α* on gap separation for Mo-Ti, Mo-Mo, and Ti-Ti electrodes. Enhancement factors at a gap separation of zero are obtained from the F-N plot using estimated primary field emission data.

again the reliability of equation (1) for evaluating field emission dark current.

## SUMMARY

Electrodes of Mo and Ti were fabricated and tested. A new analysis method was proposed to evaluate the primary field emission current component of the total dark current by using gap dependence data. Through this analysis, it was predicted that Mo is most suitable as a cathode material, while Ti is suitable for use as an anode. This is verified by experiment using the electrode configuration of a Mo cathode and Ti anode. A dark current of 1 nA was generated under an applied field of 130 MV/m at a gap separation of 0.5 mm. This result is useful for constructions of high field gradient guns to produce the low emittance electron beam in various applications. The details of this report will be published in a referred journal [5].

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