The role of front electrode in electron emission from ferroelectric cathode

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Abstract. Electron emission from ferroelectric cathode (FEE) is unconventional electron emission effect. Experimental studies on ferroelectric emission (properties of PLZST antiferroelectric ceramics samples) at room temperature and in low vacuum had been carried out. Both islands electrode and stripes electrode were used in experiments. The influences of front electrode patterns on electron emission were investigated by measuring the emission current from the sample. It had been found that different patterned front electrodes yielded different emission current. The islands electrode emitted lower current than the stripes electrode.

1. Introduction

Ferroelectric cathodes had been widely studied over the last twenty years. Electron emission from ferroelectric cathode (FEE) was unconventional electron emission effect. It was well known that the application of a high- pulse of $10^5 – 10^6$ V, with $10^{-9} – 10^{-6}$ s pulse duration, between a cathode and an anode placed in vacuum, led to the generation of high current electron beams.

Although many studies about FEE had been carried out, little researches had been done to focus on the role of front electrode in electron emission. Different patterns were used by different groups, such as stripes, islands, grids and so on. Electric-field distributions over the ferroelectric cathode surface were simulated in the work of Jihoon Park et al. [1] and Rosenman et al. [2]. They found that different parameters of patterned front electrodes formed different field distributions. It was implied that different front electrodes would yield different FEE performance.

In this article, experimental results of ferroelectric emission obtained with different electrode pattern were reported. Antiferroelectric PLZST cathode placed in an electron emission configuration was used to generate electron beam. Two kinds of patterns, stripes and islands, had been investigated. We preliminarily focused on the FEE with driving pulse voltage and bias voltage of 0V–4000V. It was found that different patterns yielded different FEE currents.

2. Experiment setup

2.1. Equipment

Figure 1 showed a schematic diagram of the experimental setup. Antiferroelectric (AFE) samples were placed in the vacuum chamber with front patterned graphics electrode (GE) facing down to the flat
graphite collector (GC). The front electrode was kept at ground potential, while the driving pulse was applied to the rear electrode. The distance between the sample and collector was set at 5.3 mm. The graphite collector area was 1.5 times larger than the emission area. A DC high-voltage generator was connected to the anode (graphite collector) to apply an external accelerating voltage (DC bias voltage) through the diode gap.

A cable with an impedance of 50 $\Omega$ was soldered on the electron collector and connected to the measurement circuit; the emission electrons were collected and flowed through the 50 $\Omega$ resistor. A Pearson Rogowski current monitor model 65/85 was used to measure the emission current from the surface of AFE sample. A 0.1 $\mu$F capacitor was inserted behind the anode, decoupling it from ground for the application of DC bias voltage. The decoupling capacitor acted as a short circuit for the short current pulses, thanks to the high value of its capacitance. A two-channel digitizing real-time oscilloscope (Model TDS 460, Tektronix) with a 500 MHz bandwidth was used to measure the voltage across the AFE sample and the current through the Pearson coil. To minimize electrical noise, all connector cables were electromagnetic shielded and connecting line were made as short as possible [3].

![Schematic circuit of the experimental setup](image)

**Figure 1.** Schematic circuit of the experimental setup [3]

Current emission was successfully achieved with both stripes and islands patterned electrode with unipolar driving pulses applied to rear electrode. For convenience, these two samples were called stripes sample and islands sample, respectively. Only three parameters were used in this paper: driving pulse voltage, bias voltage, emission current peak. All experiments were carried out with the same positive polarity driving pulse voltage of 1200 V and the pulse duration was 1000ns. DC bias voltage ranged from 0 V to 4000 V. With every bias voltage, both stripes and islands sample were tested and the emission current was recorded.

All tests were performed in a vacuum of 5.0–7.0×10⁻¹ Pa and at room temperature of 25 °C.

2.2. Materials
The samples used in the present study were antiferroelectric ceramic disks ($Pb_{0.94}La_{0.4}(Zr_{0.53}Sn_{0.30}Ti_{0.17})O_3$, 21.0 mm in diameter and 1.0 mm in thickness) prepared by a traditional solid-state reaction process. This composition was near the ferroelectric-antiferroelectric phase boundary.

Figure 2 showed the typical double hysteresis loop of antiferroelectrics. Hysteresis loop characteristics of PLZST were measured at room temperature by using improved Sawyer-Tower circuitry before electron-emission measurements.
Figure 2. Hysteresis loop of PLZST measured with 1Hz sine-alternating voltage applied (2500V)

2.3. Electrode and Geometry
After ultrasonic cleaning in water, samples were patterned with a grid silver electrode on the front side and a solid electrode on the rear side. Figure 3 (a), (b), (c) demonstrated the front electrode and the rear electrode of experimental samples. Front electrode patterns consisted metal stripes or islands surrounded by a metal ring (outer diameter 17.0 mm, inner diameter 11.0 mm) and the rear electrodes were 15.0 mm in diameter. For stripes, the wideness of silver electrode and bare ceramic spacing in

Figure 3. Sketch of the electrodes: (a) front electrode: a grating interconnected by a metal ring, (b) front electrode: a distribution of islands surrounded by a metal ring, (c) rear electrode.
the grid pattern was 0.2 mm. For islands, every metallic dot was 0.2 mm in diameter with interval of 0.2 mm. Thereby the total bare area on the surface of these two patterns was about 0.475 mm\(^2\) and 0.764 mm\(^2\), respectively.

The silver electrodes were obtained on the center of the disks by screen printing technique and sintered at temperature 820 °C for 10 minutes. And the thickness of the silver electrode was about 10 μm. Many micro protrusions might always exist on the cathode surface and they had a typical size of several microns. And the front electrode was connected to the experiment circuit through the metal ring.

3. Experiment result

3.1. Waveforms (Pulse voltage and emission current)

Figure 4 and figure 5 showed two sets of typical waveforms with low bias voltage (150V). The distinguishing feature of these two waveforms shown in figure 4 and figure 5 was the pulse voltage waveforms and emission current:

- There was a drop in the middle of pulse voltage across islands sample in figure 5 while stripes sample is not in figure 4.
- The maximal emission current of stripes sample and islands sample with a DC bias voltage of 150 V were 17.6 A and 16.1 A, respectively.

![Figure 4. Waveforms of stripes sample with bias voltage of 150V](image)

![Figure 5. Waveforms of islands sample with of bias voltage of 150V](image)
3.2. Current Peaks
Both stripes and islands sample were tested and the emission current was recorded with every bias voltage ranged from 0 V to 4000 V. Table 1 showed some of the different value of maximal currents that obtained with specific bias voltage. And figure 6 showed the complete experiment results of all maximal currents. And it could be concluded from figure 6 that the emission current was enhanced with the increasing of bias voltage. In addition, there was a linear relationship between the bias voltage and current peaks with high bias voltage.

| DC bias (V) | 0  | 1000 | 2000 | 3000 | 4000 |
|-------------|----|------|------|------|------|
| Maximal current of stripes sample (A) | 0.6 | 257  | 516  | 785  | 1060 |
| Maximal current of islands sample (A) | 0.0 | 237  | 486  | 760  | 1035 |

**Figure 6.** (a) Comparison of current peak of different electrode patterns, (b) partial enlargement of (a) (0V–200V).

It could be noticed from figure 6 that there are some differences:

- The stripes sample emitted greater current than islands sample with the same bias voltage.
• The stripes samples started to emit a current of 2.4 A with the bias of only 50V. In contrast, islands samples started to emit current when a bias of 140V was applied.
• There was no significant difference in current peak between the stripes sample and the islands sample with high bias voltage.

4. Discussion
It had been shown above that there were three major differences between stripes pattern and islands pattern:
• The stripes sample and islands sample produced different maximal current of emission.
• The islands sample needed a higher bias voltage to start current emission than the stripes sample.
• There is difference between the stripes sample and islands sample in waveform of voltage. Therefore, there were three aspects of discussion about the different of these two electrodes.

4.1. Different maximal current produced by different electrodes
Angadi et al. [4] and Shannon et al. [5] suggested that FEE was induced by polarization reversal. Electric field enhancement on the edge of metal grid resulted in weak emission to produce surface plasma. Boscolo and Cialdi [6] held that FEE was induced by the field emission in the vicinity of the metal–insulator–vacuum triple point, and emitted electrons was not high enough to ignite the surface flashover.

According to our experiment, it was obvious that there was more bare ceramic area on the islands sample. Ratio of bare area of stripes and islands was presented as in equation (1):

\[
\frac{\text{Bare Area}_{\text{stripes}}}{\text{Bare Area}_{\text{islands}}} \approx \frac{0.475 \text{mm}^2}{0.764 \text{mm}^2} \approx 0.62
\]  

(1)

If polarization reversal affected FEE, the islands sample should have emitted larger current. In fact, however, the islands sample emitted lower current.

Compared with stripes electrode, islands electrode had less effective triple points (less triple-junction area). For the stripes pattern, all stripes were interconnected by the metal ring. Therefore, both two borders of every stripes would be effective triple points. For the islands pattern, all islands could be considered as electric insulated. A brief calculation demonstrated as in equation (2) would show the difference of triple-junction area:

\[
\frac{\text{TriplePoint Area}_{\text{stripes}}}{\text{TriplePoint Area}_{\text{islands}}} \approx \frac{L_1 \times \Delta}{L_2 \times \Delta}
\]

\[
\approx \frac{1}{2\pi R} \left( \frac{1}{2} \times 2\pi R + 2 \times \sum l \right)
\]

\[
\geq \frac{1}{2\pi R} \left( \frac{1}{2} \times 2\pi R + 2 \times (26 \times \frac{1}{2} \times 2R) \right)
\]

\[
\approx 8.8
\]

\[\Delta\], the hypothetical width of effective triple area;
[R]: the radius of electrode area;
26: there are about 26 stripes in that pattern.

4.2. Threshold voltages needed to start electron emission
It could be explained by the same reason discussed in section 4.1. Application of a voltage pulse to the rear electrode leaded to the appearance of a quick polarization reversal. The strong force of repulsion
caused the intense electron emission from the front electrode. Further, explosion emission took place because of the extremely high electron current density [7]. The explosion process caused the formation of a neutral cloud, which was simultaneously ionized by electrons, leading to the formation of plasma.

The plasma moved towards the graphite anode after formed on the ceramic surface due to electron avalanching. The islands electrode formed less plasma than the stripes electrode because of less triple-junction area with the same driving voltage. So there was little plasma after plasma closure. Then very little plasma reached the anode with low bias. Therefore, the plasma could be too little to be measured by the oscilloscope.

So it is hard for islands electrode to ignite surface flashover. Higher driving voltage was needed to start electron emission. Moreover, on the same experimental condition, islands electrode produced less initial plasma near triple points. Low bias extracted less charge from the surface plasma. So less current even zero amperes were collected with low bias voltage.

4.3. Reason for drop of waveform of voltage
The differences in waveforms related to the capacitance of PLZST samples. While the driving pulse was applied to the electrode, the effective metallic electrode area of island sample was much less, than the stripes sample. Only the metallic ring was available to serve as electrode in island sample. As a result, island sample was easier to be charged by the given voltage source equipment than stripes sample.

Then the plasma extended across the sample surface with a velocity of 10 – 15 mm/μs after produced by surface flashover [8]. Therefore, plasma would cover the whole sample surface within 350 ~ 500 ns (the radius of the sample was about 21mm). The plasma might serve as a dynamic electrode to provide an additional electrode area because of the conductivity of the plasma. So the area of effective electrode expanded.

\[ C = \varepsilon \frac{A}{d} = \frac{Q}{U} \]  

The area of electrode \( A \) increased extremely fast, thereupon the capacitance \( C \) increased instantly. On the other hand, \( Q \) could not change immediately, so the voltage \( U \) across the sample had to be diminished. Then the voltage source kept on charging the sample. The voltage increased to the preset value subsequently. It was that how a drop on the waveform of voltage was produced.

5. Conclusions
The patterns of the electrodes did affect the performance of ferroelectric emission. Compared with the more common stripes electrode islands electrode was inefficient:

- Islands electrode emitted lower maximal current especially with lower bias.
- Islands electrode needed higher driving voltage to start electron emission.

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