CHAPTER 4
DEGRADATION OF FIELD EMITTER ARRAYS

4.1. Introduction

In this chapter, the results of the experimental measurements on the \( \text{O}_2 \) degradation of active Mo FEAs are presented. From the Fowler-Nordheim (F-N) curves, before and after degradation, the relative changes in the slope and \( y \)-intercept were calculated. B.R. Chalamala et al. has reported the degradation in emission current due to \( \text{O}_2 \) exposures on Spindt type FEAs.\(^1\) \( \text{O}_2 \) is present within the device envelope and readily interacts with Mo forming Mo oxides.

Emission degradation of the field emission cathodes can occur in many ways. Adsorption of gases on the tip surface can result in a work function change, thereby changing the emission. High field-induced chemical reactions also play an important role in determining the surface chemistry and physics of these devices during their operation.\(^1\)

In a typical Spindt cathode array, the gate to tip spacing is about 0.5\( \mu \)m. For gate voltages of 50-100V, electric fields as high as \( 10^8 \) V/m can be achieved near the tips. With such high fields, field dissociation of gases can occur near the emitter surface. The resulting ions and free radicals can further modify the surface of the tips and change the work function and therefore the emission current.\(^1\)

4.2. FEA Activation - Tip Conditioning

The FEAs are activated (i.e. run for several hours at a constant current), using a simple Current controller created in Labview 6.0\(^2\) (see Appendix). A screen view of a tip conditioning experiment is shown in Figure 4.1.
4.2.1 Tip Conditioning at constant Current

Initially the FEAs required a high gate voltage (80V) to start emitting. By applying a voltage, there is some tip cleaning due to field desorption and removal of the oxide layer, which results in an increase in emission current for the same voltage. However, too much emission current from the tips changes the tip geometry.

Array Conditioning at Constant Current

Figure 4.1 Screen view of a tip conditioning experiment done at constant current of 1mA. The initial gate voltage was 60V reducing to 56V after 2 days.

Tip conditioning is not done at a constant gate voltage because, as the tip gets cleaner, the work function reduces resulting in a large increase in emission current. For this reason, tip cleaning is done at constant current using a feedback controller, which automatically adjusts the gate voltage to get the set point value of emission current.
The initial gate voltage required to get 1mA was 60V and after 80000 s (1 day), the voltage dropped to 56V. The array was then switched off for 3 days and the above process was repeated for a higher current.

**Array Conditioning at Constant Current**

![Array Conditioning Graph](image)

Figure 4.2 Tip conditioning for a stable FEA, being conditioned at 3 mA. Even after one day, the change in voltage was < 1V (i.e. the tip was quite stable).

The tip conditioning of a stable FEA, cleaned for 2 days is shown in Figure 4.2. In order to understand the effect of conditioning on the emission characteristics of the FEA, several I-V and F-N plots were recorded during the course of the experiment. The pressure of the UHV test chamber was $3.0 \times 10^{-8}$ torr before switching on the array.
4.2.2 Tip Analysis (I-V and F-N data)

In order to measure the emission characteristics of the FEA, several I-V and F-N plots were acquired. The F-N plot provides an indication of the work function, tip geometry (slope of the FN plot) and average emission area (y – intercept of the FN plot) as seen in Figure 4.3.

Figure 4.3 I-V plots taken before and after the FEA was conditioned. As we ran the FEA for longer periods of time, we see tip cleaning in the form of higher emission current for the same voltage.

To get an idea of the tip geometry, work function and emission area, F-N plots are shown in Figure 4.4. We ran the experiment for a week, starting on day 0 we took an I-V plot and then on day 1 (24hrs) and day 2 (48hrs). We switched off the FEA on day 3
(72hrs) for 3 days i.e. we switched on the FEA on day 6 (144hrs). Then we again conditioned the FEA from Day 6 (144hrs) to Day 7 (168hrs), after which we switched off the FEA. The above tip conditioning, was done at a constant current of 1mA. The initial gate voltage needed for 1mA was 60.16V. During the tip conditioning process, the gate voltage was reduced (as the tips got cleaner) and reached 56.32V after 48hrs of operation (day 2).

![Fowler-Nordheim Plots during Activation](image)

**Figure 4.4** F-N plots taken before and after the FEA was tip conditioned. As we ran the FEA for longer periods of time, we see tip cleaning (reduction in slope and lowering of the emission area).

During tip conditioning, there is a reduction in slope and emission area (reduction in work function, due to cleaning since the tip geometry does not change for small O₂
exposures\(^1\)). When we switch the FEA off, from the 3\(^{rd}\) day till the 5\(^{th}\) day, there is an increase in slope due to some tip oxidation, which is less than the starting value as the FEA was in UHV i.e. 3.0 \(\times 10^{-8}\) torr. There was a considerable increase (almost 7 times) in emission area as indicated by the FN plot Y – intercept. This can be attributed to more tips emitting.

When we do another tip conditioning experiment from day 6 (144hrs) to day 7 (168hrs) and we see a reduction in the slope due to cleaning and a reduction in emission area (almost 3 times) which may be due to the reduction of the number of emitting tips.

4.3. DC Mode Degradation – Experimental

4.3.1 Degradation as a function of Gate Voltage

![Figure 4.5: \(I_N\) - t plots for different Gate Voltages](image)

Figure 4.5 \(I_N\) - t degradation as a function of initial gate voltage in DC Mode
The DC mode degradation experiments were done for different initial gate voltages (48V, 50V, 52V, 54V and 56V). This was done to determine whether the arrays could be stable in O\textsubscript{2} if they were run at lower voltages. The FEA was first tested for emission current stability for 5000s (to have less than a 0.5% change) before exposing it to O\textsubscript{2}. After the degradation experiment, the O\textsubscript{2} was pumped out and the gate voltage was increased to a higher value (slightly higher than the gate voltage required for the next experiment).

In view of the coupled nature of these interactions, it is not possible to separate the effects due to the high electric field and the field emitted electron density. The degradation in emission current after 20000L O\textsubscript{2} exposure was measured for different gate voltages (48, 50, 52, 54 and 56V) and is presented in Figure 4.5. The initial anode currents were not the same and varied from 0.6mA to 3.3mA.

The degradation as a function of exposure follows an exponential behavior at low exposure doses until 5000L after which it follows a linear relation. The extent of degradation increases as a function of gate voltage, from 86% at 48V to 97% at 56V, which is almost a 11% increase in degradation.

4.3.2 Changes in Slope & y - intercept

In order to relate the emission characteristics to the surface properties, the changes in slope and y - intercept, after every exposure were measured. Changes in work function or tip geometry are reflected in the slope of the F-N plot and the changes in area are reflected in the y - intercept.

In the field emitter arrays tested, a layer of amorphous Si is placed below the Mo emitters as seen in Figure 4.6, for current limiting, and thereby preventing catastrophic
failures. The resistance of the amorphous Si layer affects the emission current. Therefore, to accurately calculate the changes in work function, the voltage drop across the amorphous Si layer has to be taken into account.

Various models for estimating the resistance for such arrays have been proposed\textsuperscript{3,4}, but it was found that by fitting the data in a low emission current regime, the perturbation induced by the resistive layer on the slope can be avoided and we can get good estimates of the value of the F-N curve.

![Figure 4.6 Schematic of a typical Spindt-type Mo Field Emitter Array\textsuperscript{5}](image)

As we go to higher voltages, the emission current starts to turn over. This is due to current limiting effect of the amorphous Silicon layer as shown in figure 4.7, which also helps in maintaining current uniformity from the tips, and thus preventing catastrophic failures due to high emission current from the emitting tips.

Since the FEA was exposed to 20000 L of O\textsubscript{2}, the change in the slope of the F-N plot after each degradation experiment was significant. There is also a significant change in the tip geometry, apart from the change in work function and emission area as shown in Table 4.1.
Figure 4.7 I-V Curve for higher voltages. At higher voltages, due to the amorphous Si layer, there is a current limiting effect.

<table>
<thead>
<tr>
<th>Day</th>
<th>$V_g$ (V)</th>
<th>F-N Slope</th>
<th>F-N Y-intercept</th>
<th>% Change in Slope</th>
<th>% Change in Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>-420.1</td>
<td>0.6</td>
<td>44.9%</td>
<td>568.6%</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>-419.1</td>
<td>1.0</td>
<td>49.7%</td>
<td>305.5%</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>-418.1</td>
<td>2.0</td>
<td>58.9%</td>
<td>64.9%</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
<td>-417.1</td>
<td>2.0</td>
<td>62.6%</td>
<td>-9.5%</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>-456.3</td>
<td>2.2</td>
<td>44.5%</td>
<td>-63.2%</td>
</tr>
</tbody>
</table>

Table 4.1 Change in the F-N Slope and y-intercept after O$_2$ degradation experiments for different Gate Voltages.
The change in F-N Slope after the O\textsubscript{2} exposure, assuming all the Mo forms MoO\textsubscript{2}, would be 41.6\% (from 4.6eV to 5.8eV). From our results we see a higher % change, which indicates that apart from the change in work function due to oxidation, there is also a change in tip geometry.

4.4. Estimating the Life of the FEA

To get an idea of the lifetime of the FEA, we do a linear fit from 22000s to 25000s of degradation time (since the I-t plot is linear) as shown in figure 4.8. The mean lifetime $\tau$ is the solution extrapolating the straight line to zero emission current.

Each time we did a degradation experiment for 20000 L (20000s at $1.0 \times 10^{-6}$ torr), there was a reduction in the estimated value of the lifetime. The reduction in lifetime after each experiment was not a constant and varied from 2000s to 11000s. The possible explanation was that as we did more experiments on the same FEA, there was some permanent change in tip geometry as seen in table 4.1.

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>$V_g$ (V)</th>
<th>$I_a$ (mA)</th>
<th>Life (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>0.659</td>
<td>57524</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.944</td>
<td>55596</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>1.398</td>
<td>44373</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
<td>1.689</td>
<td>38621</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>3.333</td>
<td>31410</td>
</tr>
</tbody>
</table>

Table 4.2 Summary of the mean lifetimes of the FEA for the given set of 5 degradation experiments for different initial gate voltages.
4.5. Pulsed Mode Degradation – Experimental

Measuring the degradation in dc mode results in 200x acceleration in device lifetime testing (assuming a 0.5% duty cycle for normal operation), provided emission degradation depends only on total exposures and not on duty cycle. Degradation measurements were made in the pulsed mode at 100 Hz with “ON duty Cycles” of 0.5%, 1.0%, and 5% compared to the dc mode of operation (100%).
“ON duty cycle” is defined as the fraction of time the device is on to the total operation time (ON time + OFF time). In our experiments, the exposure dose, is the “nominal exposure dose” which is not the same as “true exposure dose” as shown below:

A) **Nominal Exposure Dose (L)**: It is simply the area of the P-t curve when pressure is expressed in ????? Torr and time in s. It does not take into account the % duty cycle, so a 20000L degradation experiment, done at 0.5% duty cycle and at 100% duty cycle would have the same nominal exposure dose of 20000L.

B) **True Exposure Dose (L)**: It is the product of the nominal exposure dose and fraction of the ON duty Cycle. A 20000L degradation experiment, done at 0.5% duty cycle would have a true Exposure dose of only 100L.

4.5.1 *Degradation as a function of initial Anode Current*

The pulsed mode degradation experiments were done for initial anode currents of 23mA, 31mA and 40mA. The gate voltages corresponding to these currents were 55V, 59V and 64V. The “ON” duty cycle was set to 0.5%, with an “ON” time of 50ms and an “OFF” time of 9.95ms. The FEA was conditioned for 3 days until there was stability in emission current. Before each degradation experiment, the FEA was run for 5000s to check for stability (<0.5% change in emission current).

The I-t degradation graph is shown in figure 4.9. There was very little difference in the extent of degradation for the above anode current values since the extent of degradation is strongly dependent on the initial gate voltage rather than the initial anode current. For 23mA, there was about 72% degradation, for 31 and 40mA there was about 77% degradation in emission current. To get an idea of the extent of degradation in the pulsed mode and DC mode, both I-N-t graphs have been superimposed (figure 4.10).
Figure 4.9 Pulsed mode $I_N - t$ degradation at 0.5% duty cycle for different anode currents.

Figure 4.10 $I_N - t$ plots for the $O_2$ degradation experiments in DC mode and pulsed mode at 0.5% duty cycle.
4.5.2 Anode Current Recovery

After each of the above degradation experiments, the O\textsubscript{2} was pumped out from the UHV chamber and the duty cycle was increased to 25% at the same voltage. The time of recovery to 100% emission current took over 10 hours after which it was stabilized at constant anode current for several hours.

Figure 4.11 Graph showing normalized anode current recovery after the O\textsubscript{2} was pumped out of the UHV chamber.

4.6. Results and Discussion

All the Mo FEAs have shown significant degradation in emission current when exposed to O\textsubscript{2}. Their I-V emission characteristics were measured before and after the O\textsubscript{2}
degradation experiments. For the degradation experiments done in DC mode and later in the Pulsed mode, we observed that the extent of degradation was higher in DC mode than the pulsed mode experiments at 0.5% duty cycles, which indicated that oxidation occurred even when the device was “OFF”.
REFERENCES

5 B.R. Chalamala, Thesis (PhD.), University of North Texas 1996.