Observing Performance of Individual Metal-Coated Silicon Field-Emitters in an X-ray Generator

Gil Travish*, Aquila Mavalankar, Jamie Cameron, Manuel Fohler, Isabel Gomes, Silvia Sottini and Nivedita Yumnam

Adaptix Ltd
Begbroke Science Park, Centre for Innovation and Enterprise (CIE), Woodstock Road
Begbroke, Oxfordshire, OX5 1PF UK
*Email: gil.travish@adaptiximaging.com

Abstract: *The performance of a field-enhanced emitter (FEE) array in an enclosed and ex-situ operated device has long been known to deviate from the ideal characteristics observed in laboratory settings. Here we report on the performance and failure mechanisms measured in FEE arrays operating in high-voltage sealed x-ray generators. The emitters are fabricated from etched silicon forming pyramids which are coated with metal. Unlike many previously reported arrays, here the pitch is large (1cm) and affords easy measurement and diagnosis of individual emitters. We report on emitter performance and likely causes of deviations from ideal, including the impact of anode treatment, emitter geometry and catastrophic failure mechanisms.*

Keywords: X-ray; digital tomosynthesis; field-enhanced emitters; devices.

Introduction

Field-enhanced emitter (FEE) arrays have been studied for use in a variety of devices including microwave and x-ray generators. It is generally known that field emitters are sensitive to the operating environment, with vacuum and contaminant conditions being of particular significance. These operating conditions are often reported [1] to cause a large deviation in the device characteristics expected by both theoretical predictions and those observed under ideal laboratory conditions to those measured within a final device. While the mechanisms for the performance deviation vary—and are speculated to include changes to work-function, surface morphology and tip geometry—the actual impact on the FEE array can be difficult to diagnose as the emitters are often closely spaced (~1µm).

Our team has been developing FEE arrays with large spacings between emitters (1cm) and large current per emitter (>50µA). These devices afford easy access to each emitter's performance, and the emitter-emitter interaction tends to be electrical and environmental (macroscopic) rather than parasitic (mesoscopic). These arrays have been incorporated in a set of enclosures—from actively pumped laboratory vacuum chambers to brazed, sealed units for the final product. The environment of these chambers varies in geometry, vacuum levels and bake-out temperatures, but are repeatable and predictable in their performance. Because the systems are in use as x-ray generators, they operate under high voltage (60kV) and under the associated backgrounds of scattered and secondary electrons, ions, arcs and radiation.

As a result of the relaxed emitter pitch and the multiple-housing types, we have been able to measure array performance at the individual emitter level, including during operation, and to easily SEM image each emitter before and after operation. This paper reports on the findings of large sets of emitters operated under various conditions.

The Emitter and Array

The standard array: The emitters are fabricated by etching silicon and creating "pyramids" on a 7x7 grid with 1cm spacing between emitters (Fig. 1). A standard array has 45 emitters as the corners are eliminated.

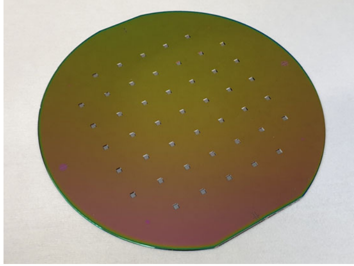
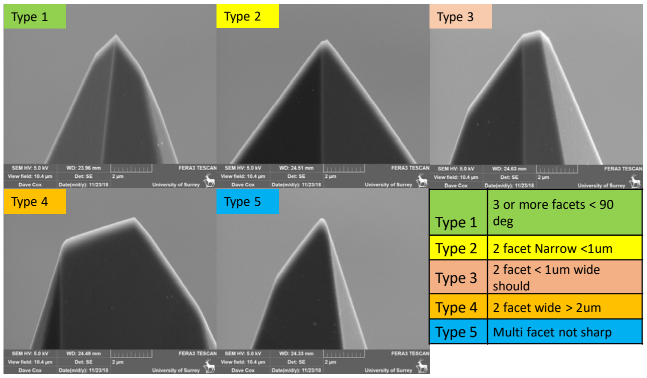


Fig. 1. Optical image of our standard FEE array. Device uses a full wafer.

A typical emitter: Each emitter consists of a pyramid formed by the silicon etch planes, meeting at a point or wedge (Fig. 2). The tips are coated with a thin layer of metal, designed to aid in thermal management [2,3] and impacts the work function and other emissive properties (Sec. III). An emitter is large (~100µm height and width) and can vary from a sharp (<100nm) point to a wedge (2-3µm) due to etch variations. These emitter variations mean that on a typical array, not all emitters would be expected to operate, and some operate well below specification. While the process-controls to eliminate variation are an area of active work, the current generation of arrays affords a means to probe the impacts of tip variation on performance and failure.



Type 1	3 or more facets < 90 deg
Type 2	2 facet Narrow <1um
Type 3	2 facet < 1um wide should
Type 4	2 facet wide > 2um
Type 5	Multi facet not sharp

Fig. 2. SEMs of five emitter tips with varying defects.

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Array Performance

Adaptix has measured hundreds of emitter arrays under a variety of conditions. Some studies focus on changes to the production aspects while others concentrate on the conditioning (“seasoning”) regime or environmental conditions (good vacuum; contaminants, etc.). Enough data has been gathered to have some consistent data sets for some parametric comparisons and for understanding gross impacts on array performance.

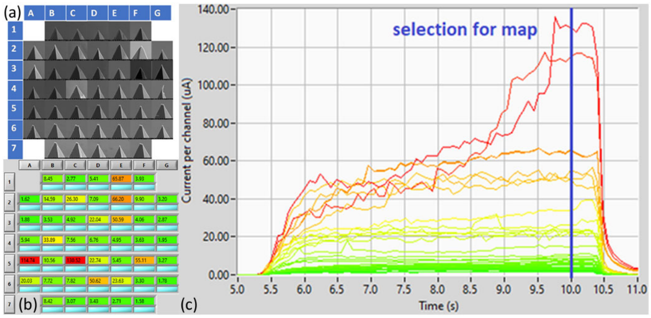
Before and after emitter comparisons: We have examined individual emitters under high-resolution SEM before operation, after conditioning and after extended operation to understand what a “good” emitter looks like and what causes emitter failure. Emitter tip shape, at the level determinable by the SEM:

- is not a predictor of quality: Both point and wedge emitters can function at high current levels.
- is not a predictor of failure: Both point and wedge emitters can fail during conditioning or operation. Typically, emitter failure is caused by thermal heating, as reported in our earlier work [2,3].
- is not a predictor of functional output. Similarity in morphology did not always equate to similar functional output.

Parameters beyond morphology are under investigation including coating variation and composition.

Array performance: We measure arrays using a “segmented anode” consisting of 45 anodes with individual (isolated) electrical read-out in real-time during conditioning. Some patterns have emerged:

- Emitters turn on at different voltages during conditioning: this is attributable to the variation in tip geometry, but not in an obvious way.
- Many emitters that turn on at lower voltages die during conditioning: this is because these emitters source much higher currents at increased voltages.



	A	B	C	D	E	F	G
1		8.45	2.77	5.41	65.87	3.93	
2	1.62	14.59	26.30	7.09	66.20	9.90	3.20
3	1.88	3.53	4.92	22.04	50.59	4.06	2.87
4	5.94	33.89	7.56	6.76	4.95	3.63	1.95
5	114.74	10.56	130.52	22.74	5.45	55.11	3.27
6	20.03	7.72	7.82	50.62	23.63	3.30	1.78
7		8.42	3.07	3.43	2.71	1.58	

Fig. 3. (a) Representative array of emitter tips. (b) Example of segmented anode data of 45 coated emitters during operation (values are in µA) – larger variations in performance were seen (even after conditoning) than expected from geometrical variations alone. (c) Individual I-t curves: note how two of the curves (red) show a steep increase in current during a 5 second pulse.

Impact of Anode Conditioning

Anode treatment is known to reduce out-gassing and the resulting ion back-bombardment. Less well reported are the effects of various treatments and materials. Because our device operates with all emitters producing current “on” during a long pulse (5 sec.), minimal anode-outgassing is important. We have studied a variety of materials and treatment methods that account for material thermal-limits, mechanical constraints, etc.

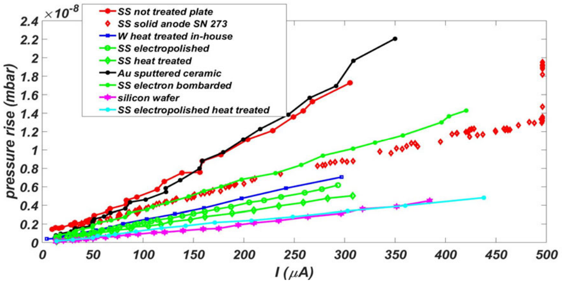


Fig. 4. Plot showing pressure rise with incident emission current for several anode materials and treatments. Note that none of the processing steps have yielded a flat (no pressure rise) curve.

Impact of Enclosure

We have studied the impact of the operating environment of the arrays. While it is not entirely possible to separate geometry, vacuum and electrical conditions we have developed a set of enclosures with similar internal electrical (anode-cathode) configurations while changing the vacuum conditions. The array-to-array variations are significant so statistical conclusions cannot be made; anecdotal observations strongly suggest that bakeouts exceeding 300°C are required to reach acceptable vacuum levels during emission (Fig. 5). Operating pressures exceeding ~1e-7mbar adversely affect the lifetime of the emitter array.

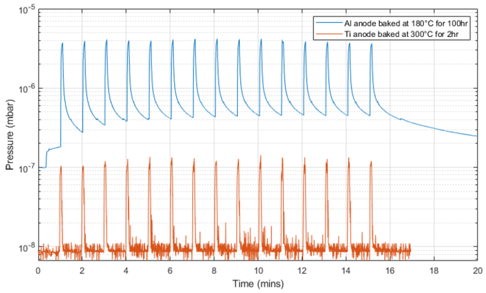


Fig. 5. Chamber pressure during a series of 2.5mA emission pulses at moderate duty cycle. Aluminium anode baked at 180°C for 100hr (blue), and titanium anode baked at 300°C for 2hr (orange).

Acknowledgment

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