

# Lifetime and reliability results for a negative electron affinity photocathode in a demountable vacuum system

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Negative electron affinity photocathodes may have useful applications as electron sources for high-throughput microlithography [A. Baum *et al.*, *J. Vac. Sci. Technol. B* **15**, 2707 (1997)]. However, the nature of such a system has raised questions about the lifetime and reliability of a cathode during operation. In this article, we report on the lifetime and reliability of cathode operation under various conditions applicable to lithography. To perform these measurements, a 632 nm laser was focused onto a spot smaller than 10  $\mu\text{m}$  in diameter on the back surface of the cathode (active area 0.5–2.0  $\mu\text{m}$  thick). The emitted electrons were accelerated to 5 kV to form a magnified image of the cathode on a phosphor screen 1 m away. The  $1/e$  lifetime of the cathode was measured as a function of the cathode current, which turned out to be an inverse relationship. Additionally, a wafer coated with SAL-601 resist was substituted for the phosphor screen to determine if resist outgassing induced by exposure affected operating lifetime. It was found that the cathode had a lifetime (75 h at 165 nA) that was the same as that obtained without the wafer under similar conditions. Lifetime was also found to be a function of initial level of cesiation of the surface and cesium levels during activation. In particular, when the cathode was initially overcesiated, the Faraday cup current (in the plane of the phosphor) was found to be stable to 2% for up to 3 days at 200 nA, indicating that the cesium level that optimizes lifetime is not necessarily the same level that optimizes quantum efficiency. © 1998 American Vacuum Society. [S0734-211X(98)08806-4]

## I. INTRODUCTION

The III–V negative electron affinity (NEA) photocathodes have been shown to have potential as electron sources for lithography and microscopy,<sup>1</sup> especially as the need for high throughput suggests the use of parallel beams. Unlike conventional electron sources such as thermionic and field-emission tips that might not provide the required consistency between different beams in the array, the flat, uniform surface of an NEA cathode would allow for multiple beams with similar properties, each independently modulated and with high brightness and low energy spread.<sup>2</sup> This attribute is attractive for an electron source in a multibeam maskless wafer exposure tool.

The NEA cathode is composed of a glass substrate with an upper layer of gallium arsenide. During the activation process, a monolayer of CsO is deposited on the surface of the semiconductor, lowering its work function and establishing NEA.<sup>3–5</sup> This allows for high quantum efficiency (QE) (the ratio of electrons emitted to photons illuminating the cathode surface) of photoemission over the entire range of visible light.<sup>6</sup> However, this layer is extremely sensitive to contamination, which destroys the NEA properties of the surface and reduces its QE.

The decay of NEA cathode current with time constitutes one of the concerns raised by the technology. In a working lithography system, it is important that the beams maintain a

constant current level for a reasonable amount of time. In order for the technology to be practical for use in manufacturing, the instrument should operate for at least 1000 h without cathode replacement. The results of this research indicate that when the various conditions that affect cathode lifetime have been properly taken into account, cathode performance is dramatically improved and such a technology becomes viable for manufacture.

## II. EXPERIMENTS

All of the experiments were performed in a demountable vacuum system built at Stanford University.<sup>1</sup> The NEA cathodes consisted of a 0.5–2.0  $\mu\text{m}$  gallium arsenide active layer deposited on a glass substrate 2.0 mm thick and 1.8 cm in diameter. The cathodes were introduced to the ultrahigh vacuum (UHV) chamber (with average pressures under  $10^{-10}$  Torr) through a specialized load lock. The activation process involved heat cleaning the surface of the gallium arsenide, and then alternating the addition of Cs and O<sub>2</sub> to form the Cs/O layer which induced a condition of NEA.

After the cathode was activated, it was transferred to the electron gun. A 7 mW HeNe laser (632 nm) was attenuated and focused down onto a spot less than 10  $\mu\text{m}$  in size on the surface of the cathode. The electrons emitted by the cathode were accelerated to 5 kV by an extracting aperture 100  $\mu\text{m}$  in diameter. These electrons were then focused and magnified by a magnetic lens onto a phosphor screen fitted with a Faraday cup 1 m from the cathode.

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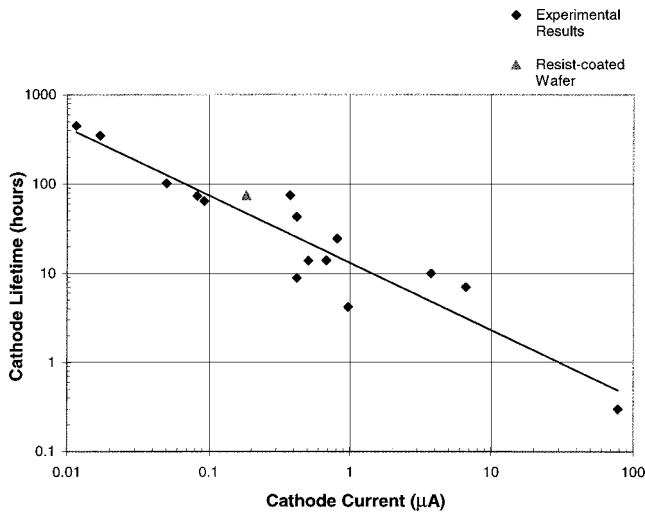


FIG. 1. Experimental results of cathode  $1/e$  lifetime vs cathode current, keeping all other parameters constant (e.g., no cesium replenishment).

Lifetime experiments consisted of focusing the laser onto a new position on the cathode and leaving it there for many hours while the currents both at the cathode and at a Faraday cup near the phosphor screen were monitored. The discussion in this article will periodically refer to these two different currents. The cathode current is measured by using a picoammeter in series with the cathode, which is at  $-5$  kV. The Faraday cup current, on the other hand, is measured with a variable voltage gain current amplifier in series with the Faraday cup and is the current that would be delivered to a wafer. In general, the cathode current is roughly 3–5 times more than the Faraday cup current.

The first experiments were performed on cathodes which had been activated with the proper balance of cesium and oxygen to establish NEA and maximize QE ( $\sim 4\%$ ). They showed that cathode lifetime is proportional to the inverse of current (Fig. 1).

For operation in a realistic system, the cathode lifetime must not deteriorate significantly when the electron beam is used to expose a resist-coated wafer. Baum *et al.* reported that the exposure of an APEX-E resist-covered wafer at 200 nA for 5 min had no effect on measured cathode lifetime.<sup>1</sup> To go one step further, a 4 in. wafer coated with SAL-601 photoresist was introduced to the analysis chamber. The beam was adjusted to deliver 100 nA and swept over the majority of the wafer (an area of  $45 \text{ cm}^2$ ) for 80 h. The lifetime of the cathode under these conditions was found to be 75 h without cesium replenishment, which is indistinguishable from the results obtained when no resist was exposed. The fact that the resist did not affect the lifetime is not surprising because the amount of resist outgassing ( $7 \times 10^{-9}$  Torr maximum) is small; the three-stage electron gun pumping system effectively eliminates the threat of cathode contamination.

Initial surface conditions also had a significant effect on lifetime performance. The cathode was run three consecutive times at  $1 \mu\text{A}$  and allowed to decay without changing the

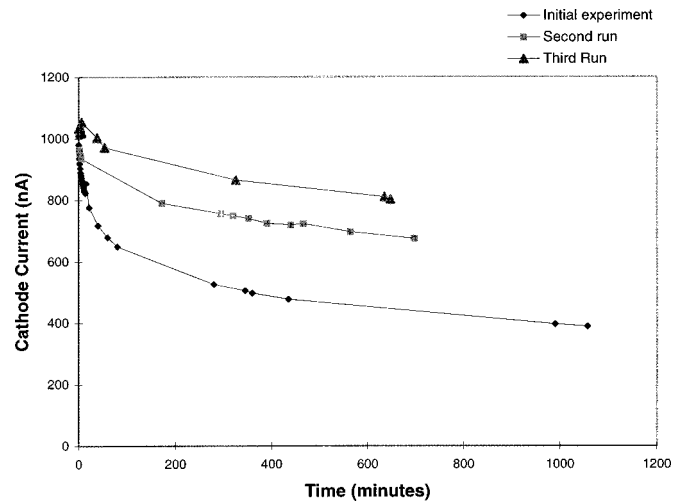


FIG. 2. Decay of cathode current with time. Three consecutive runs were performed at the same position on the cathode. At the end of each run, the laser power was increased to bring the cathode current back up to its initial value. Increasing lifetime with each consecutive run illustrates one way in which lifetime depends on the history of the cathode.

cathode position. At the end of each run, the laser power was increased by reducing the laser attenuation until the initial current was back to  $1 \mu\text{A}$  (Fig. 2). During the first run, the cathode decayed to half of its initial value in 6.1 h. On the second run, the cathode current decayed to only 66.7% of its original value even after 11.6 h, which would give it an estimated lifetime of about 2 days. When this was repeated a third time, there was a minimal decay (20% in 11 h) of the cathode current over time. However, the quantum efficiency of the cathode dropped after every experiment, which is why the laser power had to be increased to provide the same current. The formation of a “hole,” or a dead spot on the cathode surface was also observed. By the time the third run was performed, it appeared as though most emission was from regions around the dead area of the cathode.

Two main mechanisms had been identified as potential causes for the degradation in QE of the cathode surface: (1) electron stimulated desorption (ESD) and (2) thermal heating. ESD damage occurs when particles on surfaces inside the gun are released when they are struck by the 5 kV electrons and subsequently impinge onto the cathode surface. Thermal heating is damage done directly to the Cs/O layer by the laser beam. In order to separate the effect of these two mechanisms, an experiment was conducted at two different laser powers ( $50 \mu\text{W}$  and  $1 \text{ mW}$ ) in which the laser was focused continuously on the cathode while the extraction voltage was turned on and off. When the laser power was  $50 \mu\text{W}$ , no decay in the cathode current was noticed when the extraction voltage was off, even for up to 5 h. However, when the extracting voltage was turned on, current decay was observed. This implies that the extraction of electrons plays an important role in cathode decay and not thermal effects at  $50 \text{ mW}$ . However, when the experiment was repeated with a laser power of  $1 \text{ mW}$ , decay was present both during the on and the off cycles. Thus, at  $1 \text{ mW}$ , the laser

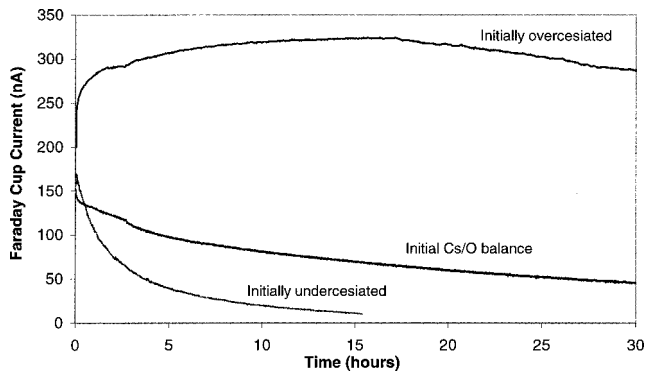


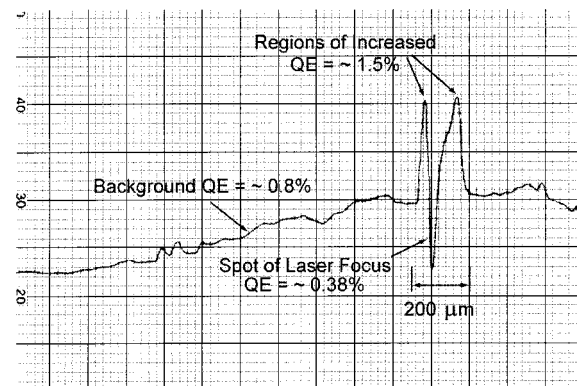
FIG. 3. Decay curves from cathodes with different initial levels of cesium on the surface. Overcesiated cathode provides the most constant current without need of external recesiation. Initial QE of these runs were all different, and so the laser power had to be properly adjusted to give an initial Faraday cup current in the 150–200 nA range.

power is high enough to start causing damage to the NEA surface. The actual contribution of each mechanism to the overall decay of cathode current at different laser powers will be thoroughly explored in future research.

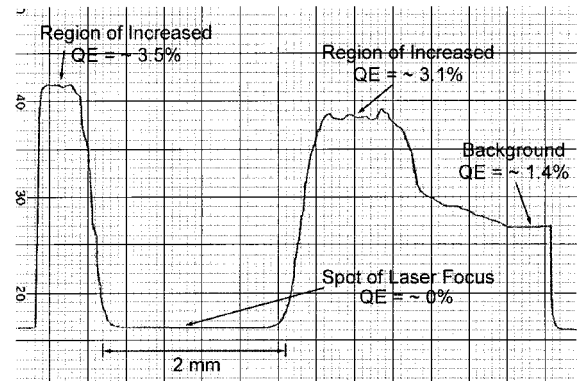
The amount of cesiation during activation was also found to affect the lifetime properties of the cathode. After normal activation to optimum QE, additional cesium was added to the surface of the cathode by firing the Cs channels for 3 min more to intentionally overcesiate the surface. With these overcesiated cathodes, the current at the Faraday cup rose dramatically in the first few minutes; in the most impressive case starting at 32 nA and rising to 4  $\mu$ A in 40 min. Typically, this rise was followed by a period of enhanced current stability lasting from several hours to many days depending on the level of cesiation and the cathode current. After the period of stable emission, the cathode current would slowly decay. Unlike the characteristic decay curve previously observed in cathodes with initial Cs/O balance, this decay was almost linear with time. Figure 3 shows a superposition of three cathode decay curves with different lifetimes. Each of the three runs were started approximately at around 175 nA down the column, and each had a different initial level of cesiation. Since the initial QE was different for each run, the laser power was individually adjusted for each run to start the initial current between 150 and 200 nA.

Several of the overcesiation experiments need to be discussed in greater detail. In the first experiment, the Faraday cup current started at 140 nA and within 100 min, climbed to 220 nA. The current then stabilized at 200 nA for 3 days without any perceptible drop in current. This result is significantly different than those obtained when the cathode had an initial Cs/O balance, where the  $1/e$  lifetime was only 12 h at this current level.

Another experiment started with a Faraday cup current of 1.5  $\mu$ A, and increased to 3  $\mu$ A in the first 100 min. The cathode then slowly decayed with a  $1/e$  lifetime of 30 h. Since usually 1/5 to 1/3 of the current generated at the cathode actually makes it down the column, 3  $\mu$ A at the Faraday cup corresponds to approximately 15  $\mu$ A at the cathode. Fig-



(a)



(b)

FIG. 4. Plot of cathode current vs position on the cathode performed with a faint probe beam (0.16  $\mu$ W). This measurement was taken after a lifetime test on an overcesiated cathode and shows the formation of interesting features in the QE of the surface. (A) The high/low/high formation is explained by the fact that electrons move around the burned spot and are emitted from the sides, removing excess Cs in those areas and improving the quantum efficiency. (B) Sweep performed after a large hole was burned in.

ure 1 shows that a cathode with initial Cs/O balance would have a lifetime of only 2 h.

After many experiments had been conducted on the overcesiated cathode, it was noted that its behavior began to change and lifetimes became shorter. Evidently, at this point, all of the excess Cs had been removed through repeated experimentation and the cathode was effectively cesium starved or undercesiated.

A sweep of the cathode surface by a fine laser probe beam (0.16  $\mu$ W) after an overcesiation run revealed interesting features (Fig. 4). Here, the Faraday cup current is plotted versus the cathode position for a constant laser power, so it is effectively a plot of QE across a slice of the cathode surface. The spot on which the laser beam was focused is marked and is a region of low QE. However, there are two regions immediately around it which have increased QE. This was an unexpected result, and a possible explanation for its formation is discussed in Sec. III.

### III. THEORY

When the cathode is cesiated with a balance of cesium and oxygen to establish NEA, the surface is easily degraded

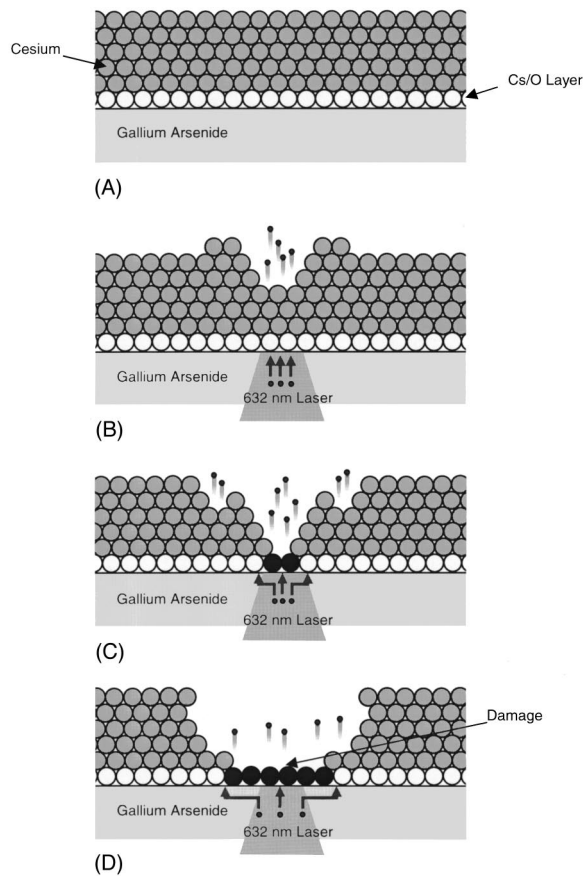


FIG. 5. Cross sections of an overcesiated cathode surface showing different regimes of operation. (A) Cathode has been activated and extra layers of cesium on the surface lower the initial QE. (B) As the cathode emits electrons, Cs diffuses from the emitting spot, improving the QE at that point. (C) QE has reached its maximum and the Cs/O layer is revealed. (D) As damage occurs, the QE of the spot begins to drop and electrons move around the spot. QE of the surrounding regions increases as excess Cs diffuses away.

and QE always goes down in time. As experimentation showed, this degradation is caused by two principle mechanisms: electron stimulated desorption and damage caused to the cathode surface by the laser beam. Of course, as the QE deteriorates the rate of decay will be reduced, and there will be a point where the QE is so poor that little change is observed in time. Little change is also noticed when the cathode currents are extremely low (i.e., approximately 10 nA).

The theory behind the operation of an overcesiated cathode is different. A distinct rise in emitted current is observed for the first hour or so, followed by a period of stability, and then eventual gradual decay. This can be understood by looking at a cross section of the overcesiated surface before the experiment begins as shown in Fig. 5. Here, the monolayer of cesium–oxide is hidden underneath several layers of excess cesium. These layers protect the monolayer, but they also block the emission of electrons and thus reduce the apparent QE of the surface. As exposure continues and electrons are extracted from the surface, the highly mobile cesium directly above the emission area is excited and diffuses away from the emission area. Thus, an increase of cathode current is noticed as time progresses for the first hour or so.

The QE reaches its maximum level once the stable Cs/O layer has been reached.

Once this happens, however, the surface no longer has additional cesium layers to protect it from ESD. The surface will begin to degrade, slowly increasing the work function of the spot and creating a “hole” in the surface. This forces electrons to go around this hole to the surrounding regions where the work function is lower in order to be emitted. This excites cesium in surrounding regions, which can diffuse back and effectively recesiate the original spot. As long as the surrounding areas can continue to feed cesium to the growing hole, there is a period of stability as seen in the experiments. The QE of the surrounding areas also rises as excess cesium is moved away from these areas, as seen in the experiments (Fig. 4).

Eventually, the diffusion of excess cesium from outside the hole will be unable to maintain a proper level of cesium at the emission spot and the output current will drop slowly. This drop is not as fast as the balanced Cs/O case, because there is still some diffusion of excess cesium. This can be considered the last region of operation for the overcesiated cathode.

The results of the overcesiated experiments are promising. The addition of extra cesium immediately after activation causes some recesiation to occur and thus induces a period of stability which could be exploited in commercial applications. In addition, direct recesiation of the cathode in the gun would also improve performance. A successful feedback mechanism that recesiates the surface and allows the cathode to emit for up to 8 h at a constant level of current between 1.64 and 1.68  $\mu\text{A}$  has been shown to work.<sup>1</sup> Recesiation works even after the cathode was exposed to a variety of gases.<sup>7</sup> All of these results seem to indicate that when these conditions are carefully controlled, lifetimes would be at least an order of magnitude longer, making the NEA photocathodes a viable electron source for lithography.

#### IV. SUMMARY AND CONCLUSIONS

Cathode lifetime and reliability has been a concern for the practicality of this technology. This article explored some of the issues that affect cathode lifetime. First, an inverse correlation between cathode current and lifetime was established for a cathode with an initial Cs/O balance. Next, initial cesiation levels were found to affect the lifetime properties. An overcesiated cathode was tested, and 200 nA was delivered to the Faraday cup without significant decay for 3 days.

Overcesiated cathodes were also found to operate in three different regimes. First, the cathode current rises with time as excess cesium is removed from the emitting spot and the quantum efficiency improves. Next, a period of stability is observed as the Cs/O is reached and the regions outside the spot provide cesium to replenish the inner regions. Finally, as the hole grows larger the cathode current slowly begins to decay.

Current lifetimes seen in our experimental apparatus would be too short for commercial applications. However, a combination of techniques to enhance lifetime including ini-

tial overcesiation, recesiation during operation, and improved gun design to minimize damage from electron stimulated desorption should allow at least an order of magnitude improvement in lifetime. When combined with the ability to move the cathode to expose a fresh area of the cathode once a part has permanently degraded, practical lifetimes in high current ( $>1 \mu\text{A}$ ) systems should be achievable. Future work is planned to demonstrate this directly.

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