Patterned negative electron affinity photocathodes for maskless electron beam lithography

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This work focuses on two issues crucial to achieving high throughput with a negative electron affinity semiconductor photocathode source. Monte Carlo simulations indicate that for a 50 kV system, as much as 8 μA of current may be delivered to the wafer to achieve a raw throughput of 20 8 in. wafers per hour with 0.1 μm minimum feature size (assuming a resist sensitivity of 10 $\mu C/cm^2$). In order to achieve the throughput potential of this approach, suboptical emission areas are required; this suggests the use of cathode patterning. Two patterning alternatives have been investigated experimentally, and both approaches have been used to generate arrays of more than 100 electron beams with source sizes as small as 150 nm. However, each type of patterned cathode presents unique challenges to fabrication and performance in a practical multibeam system. Different source configurations (number of beams, beam current, beam spacing, etc.) create a system-level tradeoff between resolution and throughput. Results from patterned cathode experiments and system modeling are presented.
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I. INTRODUCTION

A maskless electron beam lithography system based on negative electron affinity (NEA) photocathodes has been proposed in which multiplexed diode laser sources excite primary electron sources that in turn illuminate the wafer through the use of a simple, two lens, demagnifying raster projection system.[1] The enabling technology for this system is a NEA photocathode in a demountable electron gun, which has been described elsewhere.[2] One limitation of electron beam direct write (EBDW) lithography is low throughput due to electron–electron interactions which cause beam blurring at high beam currents. Monte Carlo simulations are used in this work to estimate the throughput advantage gained by using multiple beams to distribute current throughput the field of the electron optics and hence mitigate this effect. A very small (<1 μm) emission area (spot size) at the cathode is also crucial to achieving high throughput, because a smaller spot requires less demagnification for a given probe size, and hence allows for a larger fraction of current generated at the cathode to reach the wafer (current efficiency, Fig. 1). However, previous NEA cathodes have had measured minimum spot sizes of 1.5 μm or greater, limited by the diffraction limit of the exciting laser (638 nm), and spot spreading due to lateral carrier diffusion through the active region of the cathode.[2] These results suggest the use of cathode patterning in order to reduce the spot size.

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II. MONTE CARLO SIMULATION RESULTS AND OPTIMAL SOURCE CONFIGURATION

In order to model the effects of electron–electron interactions and find an optimal system configuration, several assumptions are made. A patterned NEA photocathode source is simulated, with emission properties that are needed to give 100% current efficiency. Specifically, a patterned cathode with a 0.1 μm emission area with a 0.1 eV lateral energy spread is used. In order to account for the effect of off-axis aberrations in the gun region, a total source size of 0.13 μm is used; Fig. 1 includes an off-axis error budget for up to a 1 mm field size at the source. As a result, a 1 mm fixed field size at the cathode is assumed, which corresponds to the total extent of the source beamlet array. Since electron–electron interactions are minimized when the field size of the electron optics and the spacing between beams is largest, the system configurations discussed here always use an evenly spaced array of beams at a maximum pitch (spacing between beams) consistent with this field size. It is generally assumed that to be competitive with other suboptical lithography technologies for large-volume wafer manufacturing, an EBDW should deliver a total current of 5–10 μA. In these simulations, 10 μA is taken as an arbitrary goal for total system current, and various system configurations that fit all of other constraints (50 kV system, 15 cm column length, an electron optical demagnification of 4 and 8 mrad maximum convergence angle at the wafer) are simulated.

This methodology allows for one free parameter in the simulations: the amount of current in each beamlet. Choosing this parameter also implies a selection of the total num-

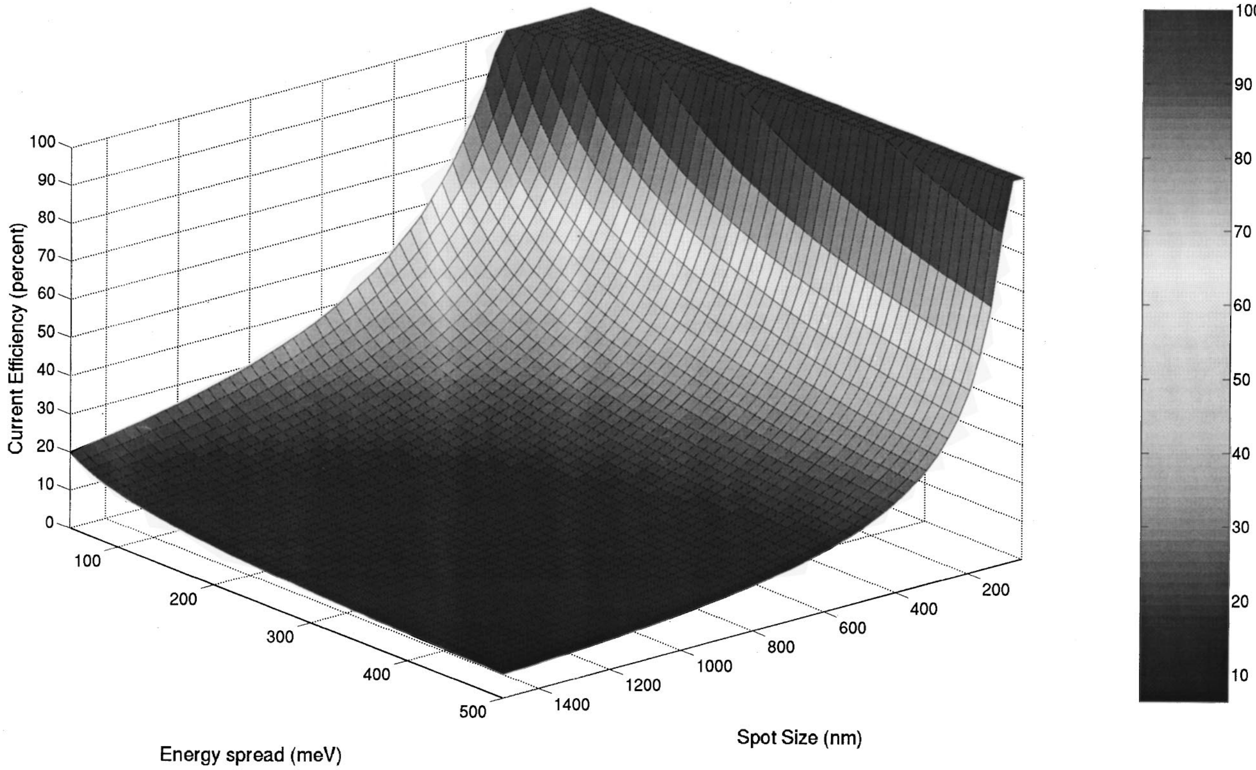

FIG. 1. Contour plot of percent current efficiency as a function of emission spot size and lateral energy spread at the cathode. As the spot size and lateral energy spread are reduced, the current efficiency increases dramatically.

ber of beamlets, as well as the beamlet pitch. For example, a system with a beamlet current of 25 nA implies a 400 (20 $\times$20) beam array (because of the 10 μA total current condition), with a 50 μm spacing between beamlets (due to the 1 mm fixed field size at the source). In the same way, selecting a 1000 beamlet system implies a 10 nA beamlet current with a 30 μm beamlet pitch. A number of simulations have been carried out which indicate that these selection criteria tend to result in an optimal system configuration.[1]

Figure 2 illustrates the results of these simulations, a plot of FW_{50} spot size (diameter within which 50% of the particles in the beam are contained) at the wafer versus the array scaling parameter described above for 10 μA total system current. The behavior of changing system parameters may be understood by examining spot size for different configurations. In the limit of a small number of beams with a relatively large amount of current per beamlet, the spot size rises nearly linearly with increasing beamlet current.[3] As has been shown in previous space charge studies,[1] an increase in beamlet current tends to have a significant impact on intrabeam interactions. When the number of beams is increased beyond a certain point, the spacing between beams exceeds the average on-axis spacing between electrons within a particular beam near the cathode. In this case, interbeam interactions tend to dominate the total blurring in the system. Therefore, an optimal value of beamlet current is apparent, which represents a balance between intrabeam and interbeam electron–electron interactions. Using a writing strategy with a hollow array of beamlets, a space charge defocusing effect discussed elsewhere[4] that causes nonuniform beamlet blurring over the electron optical field can be mitigated, allowing 8 μA to be delivered to the wafer at a spot size of 44 nm. The optimal system configuration for the hollow array strategy (15 nA per beam, 35 μm pitch) remains the same. For the purposes of comparison, if the 8 μA were distributed

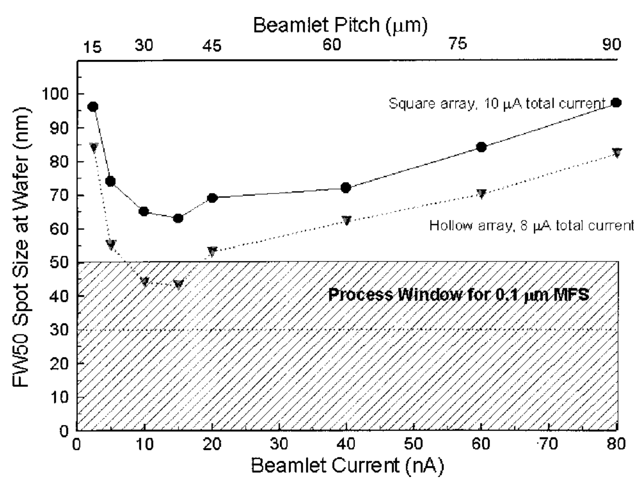

FIG. 2. Coulomb simulation results showing the throughput potential of patterned photocathodes, as well as the impact of the ''bagel'' writing strategy on system resolution. 50 kV system, 0.13 μm source size, and a 1 mm fixed field size at the cathode are assumed. Using these techniques, 8 μA total current can be delivered at a spot size consistent with 0.1 μm lithography.

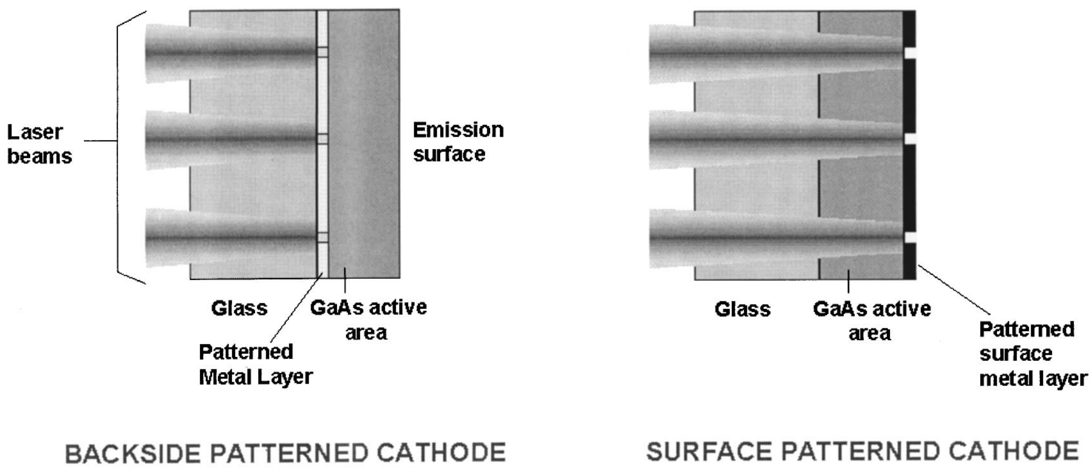

FIG. 3. Illustration of two types of patterned cathodes investigated in this work. Backside patterned cathode structure uses a metal layer as an optical proximity mask to block light from reaching the active region. Surface patterned structure uses a thin metal layer on the emission surface to change the work function at selected areas.

among 800 beams in a solid array, the maximum beamlet diameter is approximately 66 nm.

III. PATTERNED CATHODE EXPERIMENTAL RESULTS

A. Backside patterned cathode with GaAs active region

In order to establish emission from a patterned cathode structure, a backside patterned cathode is fabricated from a metalorganic chemical vapor deposition (MOCVD) grown GaAs layer [Fig. 3(a)]. In this case, a 500 A TiW metal bilayer is patterned with apertures of various sizes on an equally spaced grid. The smallest apertures resolved during the cathode lithography/etch sequence are approximately 0.25 μm in diameter. Figure 4 shows an image of the cathode surface projected onto a phosphor screen; the expanded spot size observed from the 0.5 μm apertures can be understood when the effect of lateral carrier diffusion in the active region is considered. Simulations of this cathode structure[5] indicate that although a thinned cathode structure (<1 μm thick) helps reduce the size of the resultant emission, the dominant effect remains lateral carrier diffusion.

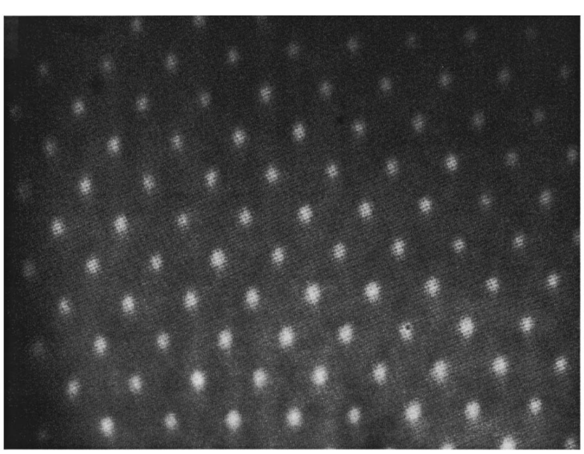

FIG. 4. Image of backside patterned cathode surface showing emission of ~100 parallel beams. Each emission area is 1.0 μm in diameter, generated from 0.5 μm apertures in the backside proximity mask. This image was obtained by flood illuminating a backside patterned cathode, and imaging the emission surface onto a phosphor screen.

Optical leakage through the metal mask and lateral carrier diffusion can lead to a blurring of the spatial profile of emitted current. Another figure of merit that can be applied to patterned cathodes is defined as contrast, the ratio of emitted current within the nominal spot to that emitted in the region surrounding the spot. For high-performance lithography, it seems likely that a contrast of 10 or above is required. For patterned cathodes with aperture sizes less than 0.25 μm, which severely attenuate transmitted optical intensity below $\lambda/2$ and limit mask opacity, contrast is severely degraded.

B. Backside patterned cathode with graded band gap region

In order to realize the performance potential offered by a backside patterned scheme, several refinements on the above design may be made. First, contrast (the ratio of current emitted within the nominal spot to that emitted outside the nominal spot) should be improved significantly to at least 10 for high-performance lithography. Second, the spot size must be made smaller by tailoring the active region to limit lateral carrier diffusion. In order to address these concerns, two major changes can be made to the original backside cathode design. The first change is the use of Pt as the material for the proximity mask. Because its transmissivity is significantly lower than that of TiW, the amount of optical leakage may be reduced significantly. An increase in the thickness of the metal mask beyond 500 Å results in an unacceptable loss in transmitted optical intensity, as well as other processing-related difficulties.

A reduction in emission spot size is the second key factor to be addressed. By using a ternary III–V alloy such as $GaAs_{1-x}P_x$ to grade the band gap in the active region and

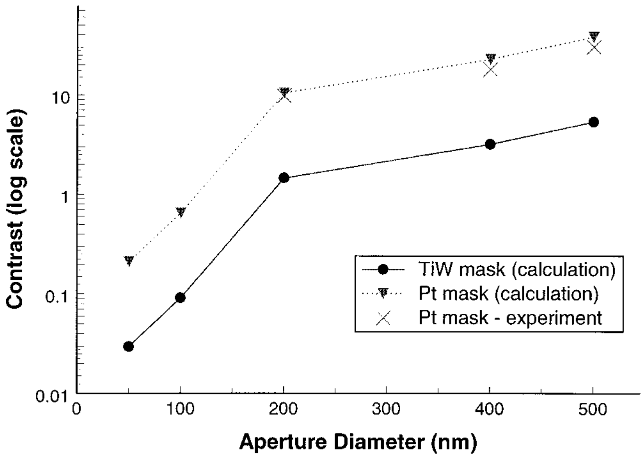

FIG. 5. Calculated and measured values of contrast as a function of aperture size for a backside patterned cathode with graded band gap active region.

decreasing the value of x from the metal mask to the surface, a built-in electric field is created in the active area. Electrons excited near the metal mask see a potential drop in the direction of the vacuum, and are accelerated in that direction. If the electrons are swept towards the emitting surface before they can diffuse significantly in the lateral direction, than a significant advantage can be obtained. This cathode employs a 500 A thick Pt bilayer optical proximity mask with a 30% phosphorous concentration active area at the mask, graded to pure GaAs at the emitting surface. The band gap grading corresponds to a 0.25 eV band gap drop over 0.5 μm thickness, for a built-in electric field of 5000 V/cm.

Using this cathode, emission spot diameters of 0.28 μm are generated from 0.2 μm apertures in the mask, with an emission contrast of 10. Using the cathode simulator described elsewhere,[5] predicted values of emission contrast for various aperture diameters have been calculated and compared alongside experimental values (Fig. 5). Predicted values of contrast are also provided for an equivalent graded band gap backside cathode with a TiW mask. It is clear from this data that the use of both a low-transmittance mask material and a graded band gap active region significantly improves cathode performance.

One obvious question about any patterned cathode configuration used in a practical multibeam system is whether the patterning process has sufficiently high yield, and is uniform over that area. To help address this question, the optical power was fixed, and the cathode current was then measured from a number of spots in the patterned region. The nominal value of current from the first 0.4 μm spot was set at 15 nA, which corresponds roughly to the amount of current required from a single spot in a high current multibeam system. With a standard deviation of less than 8% from the 25 spots measured and no significant outlying data points, it seems reasonable to assume that the patterning process is sufficiently robust to be used in a practical setting.

C. Surface patterned cathodes

While results from the backside patterned cathode with graded band gaps represent a dramatic improvement over unpatterned cathode configurations, current efficiency calculations indicate that additional gains in throughput can be made by pushing the spot size yet smaller. Due to the optical and solid state limitations described above, backside patterning techniques provide diminishing performance returns below the 1/4 μm regime. An alternative is to pattern the emission surface to directly modify the cathode surface work function on a smaller scale [Fig. 3(b)].

In electron gun measurements, surface patterned cathodes yield a moderate contrast of about 5 for spot sizes 0.4 μm or larger. However, two conditions yielded problems for the cathode performance at small spot sizes. A large number of tests on three different surface patterned cathodes show that the amount of current reaching the target (Faraday cup) is only a tiny fraction (0.5%–1%) of that emitted from the cathode for spots less than 0.4 μm. While at first this behavior seems inconsistent with operating experience from other cathodes, it can be understood in terms of electric fields at the cathode surface.

The surface work function is assumed to be relatively high everywhere except within the small apertures, where a cesiated GaAs surface is exposed. This condition implies that the drop in surface voltage must occur somewhere along the interfacial region. If the GaAs/Pt interface regions are assumed to be ohmic, then the potential drop must occur in the form of external fields which begin on the masked Pt region and terminate on the lower-work function GaAs dots. An examination of the contact potential created for a GaAs/Pt interface with surface states present indicates that the magnitude of the potential drop is approximately 0.5 V. Several different electrostatic simulations have been performed in order to assess the impact of this work function difference. When a 0.5 V surface potential difference is introduced, a significant off-axis electric field component is present near the cathode surface. This field results in a strong diverging lens around each emission spot on the cathode surface. Electrons generated away from the center of the spot are not properly imaged by subsequent optics.

Another observation is the loss of contrast seen at small aperture sizes. When an array of small dots is viewed simultaneously in the surface imaging mode, the image is quite diffuse. Since the GaAs dots are overilluminated by a diffraction-limited optical spot, about 90% of the incident optical power falls on the Pt mask region for 0.2 μm patterns. Because of the relatively low quantum yield of the GaAs dots as compared with the large unmasked GaAs areas, a relatively large amount of the total emitted current can actually come from photoemission from the Pt film itself. Cesiation of the Pt film lowers the work function considerably[6] to a point at which at 2.0 eV (633 nm) photon energy results in a quantum yield of about 7×10^{-5}. For a 0.18 μm GaAs dot with a quantum yield of 0.1%, a contrast of approximately 1.5 is predicted. Measurements on this size pattern at 633 nm show a contrast of approximately one. The

TABLE I. Summary of experimental measurements for different types of patterned NEA photocathodes.

	Unpatterned cathode	Backside cathode (no band gap ramp)	Backside cathode (with band gap ramp)	Surface patterned cathode
Brightness [A/(cm^2 sr)] at 5 kV	2.0×10^7	3.0×10^7	1.5×10^7	3.2×10^6
Lateral energy spread (meV)	80	60	65	50
Minimum spot size (nm)	1500	1000	280	150
Contrast	—	8	10	5
Current density (A/cm^2)	300	100	300	10

quantum yield of Pt (Cs) drops sharply below 2.0 eV; this trend suggests that one way of improving contrast is to increase the optical wavelength used. However, the photon energy must be high enough to provide adequate absorption in the active area. For GaAs, the photon energy must be above the band gap of 1.42 eV. If 780 nm (1.6 eV) diode laser illumination is used, then the absorption of GaAs drops by a factor of about 2, while the photoemission from Pt (Cs) should drop by approximately an order of magnitude. This gives a predicted increase in contrast of a factor of 5 at this wavelength. Experimental results show an actual increase in contrast to five (at 765 nm) from one (at 633 nm) for a 0.15 μm spot size.

D. Summary of experiments

Table I summarizes the results achieved for various measurements from different types of patterned cathodes. These results are compared for reference against the same measurements made on unpatterned cathode samples on the Stanford system. Upon examining this data, the variation in patterned cathode performance is dominated by two important factors: spot size and contrast. Although surface patterned cathodes can produce very small emission areas, the field scattering effect described earlier makes them unlikely candidates for use in a practical high-performance system. The spot size/contrast combination attained with surface patterned cathodes is limited by two factors: fabrication technology/materials, and the contrast available at a given spot size (limited by photoemission from the surface metal mask). This second factor is actually the more fundamental limitation on performance, as the size of the illuminating spot is dictated by the diffraction limit of the illuminating spot. Thus, the ratio of nominally emitting to nonemitting areas is fixed at an upper bound, governed by the light optics. Using a backside patterned cathode with a graded band gap active area produces a minimum spot size of 0.28 μm at a contrast of 10, the best overall performance level achieved in this work.

IV. CONCLUSIONS

Monte Carlo simulations indicate that for a 50 kV system, as much as 8 μA of current may be delivered to the wafer to achieve a raw throughput of 20 wafers per hour with 0.1 μm minimum feature size. In order to achieve this level of throughput, patterned cathodes are required. Backside and surface patterned cathodes have been fabricated and measured in a demountable electron gun system. The best level of overall performance (including spot size, contrast, lateral energy spread, current density, and brightness) is achieved for a backside patterned NEA photocathode with a graded band gap active area, giving a 0.2 μm minimum source size, a contrast of 10, and a current efficiency of more than 80%. Source sizes smaller than 0.1 μm might be attained, for example, by using a more sophisticated graded band gap pillar structure with a thick surrounding metal layer to maintain high contrast. All improvements in patterned cathodes, however, require a careful choice of structure and materials in order to minimize the optical, solid state, and surface constraints placed on the cathode design.

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