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We present a comparison between experimental results and computer calculations on a high current, high resolution single lens electrostatic 100 kV Schottky electron gun. One promising application for such an electron gun is for direct electron-beam patterning of x-ray masks. The high energy helps provide precise patterning of the thick resist, maintains vertical resist profiles, and minimizes the proximity effect. The gun was designed to operate from 25 to 100 kV, capable of focus at a distance of 145–245 mm with a magnification of 1.15. The emitter, of apex radius $\sim 0.6\,\mu$m operated at 1800 K in the extended Schottky regime, provides an angular intensity of 0.5 mA/sr for an extraction voltage of 5000 V and with a beam limiting aperture of 2.2 mrad, the gun delivers 7 nA of probe current. The gun consists of a replaceable high voltage optic module mounted on a precision insulator with the main acceleration occurring between the exit of the optic module and the grounded anode. A provision is made for alignment of the emitter with respect to the central optical axis of the optic module in a special alignment chamber eliminating the need for high voltage emitter alignment. Final gun alignment is achieved by X–Y motion of the grounded anode aperture. The gun is constructed to allow ease of replacement of the emitter, the beam defining aperture, and the differential pumping aperture. The beam supply has 10 ppm of ripple while lens supplies have <50 ppm of ripple. At 100 kV the power supply, cabling, connectors, insulator, and optic module draw 1 μA of ground leakage current. Pressured SF_6 chambers are used for high voltage connector interfaces within the power supply and on the gun.

I. INTRODUCTION

An electrostatically focused electron gun using a Schottky emission (SE) source has been operated at 100 kV. In addition to other potential applications, this gun is intended to be combined with a magnetic projection lens in a demagnifying mode to form a complete column for patterning x-ray masks. This application requires an electron source with high current, high resolution, and good stability. The 100 kV electrostatic gun operated in the extended Schottky regime with an extraction potential of 5 kV provides an angular intensity of 0.5 mA/sr. With a beam limiting aperture of 2.2 mrad, the gun delivers 7 nA of beam current into a crossover diameter of 46 nm. This corresponds to a current density of about 430 A/cm^2. When combined with the magnetic lens the column is expected to deliver a current density of in excess of 2000 A/cm^2.

In this article, we briefly discuss a typical application for the 100 kV SE electron gun and its design considerations. Then we present a comparison of the experimental results with the computer analysis.

II. HIGH VOLTAGE PATTERNING

While there are many potential applications for a high resolution, high current density, high voltage electron gun, one particularly promising area is the patterning of x-ray masks membranes for high resolution lithography. In one fabrication technique, a thick resist (about 1 μm) is spun onto a silicon membrane. The resist is patterned and then gold absorber is electroplated in the areas where the resist has been removed. However, with the thick resist required for this process, it is difficult to achieve high resolution with conventional electron beam lithography tools that use energies from 10 to 25 kV.

The higher energy electron beam has several distinct advantages.[1,2] First, it penetrates the thick resist without significant forward scattering. This results in vertical resist profiles which are necessary for proper plating of the absorber in the additive process. Second, most of the beam passes through the mask membrane; consequently, reducing backscattering to the point that the proximity effect may be neglected. Finally, the high energy may improve the pattern placement accuracy due to the greater immunity of the beam from stray fields although the increased heating of the deflection coil for a given field size may counter this improvement or require smaller field sizes to be used. This issue is critical to future high resolution masks with feature sizes approaching 0.1 μm where placement accuracy as high as 10 nm will be required.

III. SCHOTTKY EMISSION

Schottky emitters are well suited for use in high brightness electron microprobe applications. Such an emitter is formed

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from a ⟨100⟩ oriented tungsten wire electrochemically etched to an apex radius in a range $\leqslant 1.0\,\mu$m. The work function is reduced by the formation of a ZrO/W surface operated at 1800 K. In the presence of an electric field, a large (100) end facet is formed at the apex of the emitter. The emission regime of this emitter has been described theoretically by Swanson and Bell.[3] The emission regime is typically between that of Schottky and thermal field emission depending on the extraction voltage and emitter apex radius.[4] Thermal field emitted electrons escape from a heated metal by tunneling through the field lowered potential barrier. In Schottky emission, the electrons escape over the field lowered barrier of a heated metal.

These emitters are operated between 1750 and 1850 K to achieve emission current stability with gun pressures below 1×10^{-8} Torr. An emitter apex radius range of 0.5–1.0 μm will permit angular emission intensities in the range of 1 mA/sr with extraction voltages in the 5–10 kV range. These operational parameters provide arc-free, low noise operation resulting in a beam energy spread on the order of 1 eV.[5,6] The emission process and Boersch effect contribute roughly equal amounts to the energy spread.[7] As described in an earlier paper, a Schottky emitter in an electrostatic lens was developed and operated at 25 kV to achieve a resolution of < 10 nm.[8,9] Based on the success of the 25 kV SE experience, an effort was launched to develop a 100 kV SE electron gun.

IV. 100-kV DESIGN CRITERIA

The high voltage operation of the 100 kV SE electron gun (shown in Fig. 1) required special design considerations to minimize arcs which could damage the sensitive emitter. Within the optic module, each electric field stressed metal–vacuum–insulator junction was shielded to lower the electric field at the junction.[10] As a result, the breakdown voltage across each interelectrode gap exceeded 12 kV, which is a factor of 2 greater than the typical operational voltages.

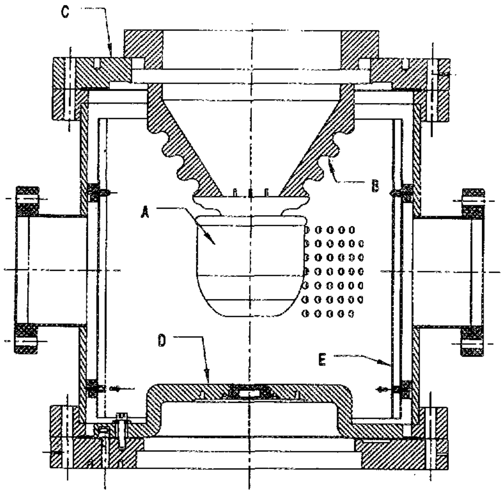

FIG. 1. Cross-sectional view of the 100 kV Schottky electron gun. The optic module (a), containing the emitter and lens elements, held on the insulator (b) which is welded to a 14-in. conflat flange (c). For beam alignment, the anode element (d) is movable. Two concentric magnetic shields (e) provide external field immunity.

Critical to high performance are good vacuum and clean surfaces. The anode plate incorporates a differential pumping aperture and the gun chamber is pumped by two 60-ℓ/s ion pumps. The gun chamber is baked at 220 °C and operated at pressures below 5×10^{-9} Torr. An array of 16 holes around the circumference of the optic module is provided to allow adequate pumping conductance in the emitter region. Pumping conductance must be balanced against the possibility of secondary electrons escaping from the module. Depending upon the radius of the emitter, the supply will typically extract 200 μA of total emission, most of which is skimmed by the extractor plate. If the 200 μA of electron flux or its secondaries were allowed to escape through the module pumping apertures, it would be accelerated into the chamber walls and main insulator. This could cause unwanted gas desorption, an x-ray background, and insulator charging. An electron suppressing cylindrical shield is built into the module to prevent primary or secondary electron escape from the module. The escape current is below the limit of measurability of 1 μA. A suppressor electrode is provided to prevent emission from the shank of the electron source. The emitter tip protrudes 0.26 mm beyond the suppressor and is 0.51 mm from the extractor.

Electrical linkage to the lens elements is made by five feedthrough pins brazed into the apex of the conically shaped insulator shown in Fig. 1. The cluster of feedthrough pins is shielded from ground inside vacuum by the large polished molybdenum module shield and in SF_6 by a shaped aluminum shield. The conical insulator is shaped with its major radius at ground potential and its minor radius at negative potential which has been shown to be a favorable orientation for preventing breakdown.[11] An SF_6 chamber pressurized to 3 psi surrounds the back side of the insulator. Inside the SF_6 chamber, a gun receptacle/socket assembly is used in the cable to power supply linkage. The 0.25 in.-thick stainless-steel gun chamber tubing and effective 3 mm-thick leaded glass viewport provide enough attenuation that there is no measurable x-ray flux from the gun when operated at 100 kV with 10 nA of beam current on a gold target.

The lens bores of the optic module are aligned by the insertion of a slip fit ceramic rod. The emitter is aligned with respect to the extraction aperture in an optical microscope; then clamped into place. The anode is mounted on a ± 0.5-mm travel motion plate to accurately align the beam into the center of the anode aperture. Deviations from proper anode alignment show up as a slight increase in the beam astigmatism.

A custom 100 kV power supply was built to provide all gun control voltages. The suppressor, focus, emitter, and extractor power supplies are housed in an SF_6 filled chamber and controlled by optical fiber linkage. Arc protection to the lens supplies is accomplished by spark gaps. Each supply was designed with ripple that would limit beam spot size blur, as determined by the computer analysis, to be < 10%.

V. ELECTRON OPTICAL DESIGN

The details of the electron optical design have been published elsewhere.[12] Here we present only a brief review of the three electrode electrostatic lens system as shown in Fig. 2.

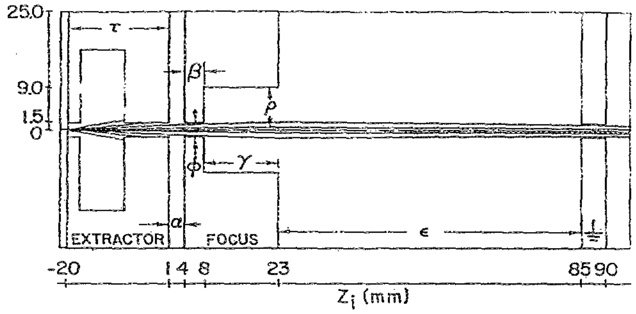

FIG. 2. Lens geometry where Zi is the distance from the emitter tip. The gap between the extractor element and the focus electrode is given by $\alpha = 3$. The length of the focus lens is $\beta = 4$. The asymmetrical focus bore is $\gamma = 15$. The distance between the focus electrode and the grounded anode is $\epsilon = 62$. The length of the extraction element is $\tau = 21$. The lens bore diameter $\phi = 3$. Not shown is a suppressor electrode which surrounds the shank of the emitter. The suppressor is typically biased at -300 V with respect to the emitter in order to prevent unwanted shank emission.

Electron current is drawn from the emitter by the extraction electrode which contains a 2.2 mrad beam limiting aperture. The asymmetrically shaped focus electrode, here operated in a decelerating mode, allows variation in the beam energy while maintaining a fixed image distance.[7,13] In order to implement conjugate blanking, the design called for forming a beam crossover beyond the anode plane at an image distance between 145 and 245 mm. Generally, in field emission electron optics, the image distance will scale as the extraction voltage. Yet, for emission stability, the range of practically available extraction voltages cannot scale with the beam energy. The gun image distance increases by increasing the distance between the focus lens and the anode; therefore, setting a minimum value of the focus to anode gap.

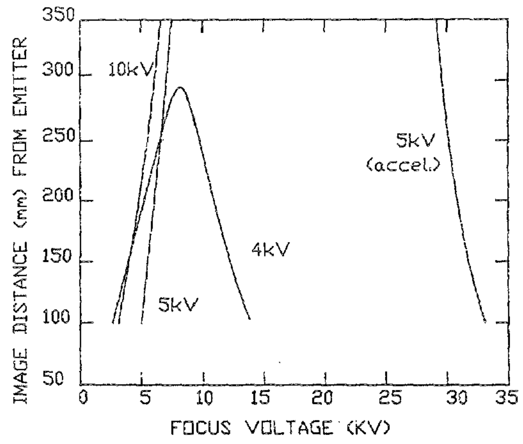

FIG. 3. Computer results of the gun image distance from the emitter tip vs focus electrode voltage relative to the 100 kV emitter voltage. The extraction electrode voltages of 4, 5, and 10 kV are shown as an independent parameter. The positively sloping curve corresponds to the deceleration mode while the negatively sloping portion corresponds to the acceleration mode. The 5 kV extraction voltage experimental data points for the focus lens voltages of 5084 and 6548 V are in reasonable agreement with the respective 145 and 245 mm image distances. Experimental deviation from the predicted values may be due to inaccuracies in the measurement of the distances.

The critical gun dimensions such as the focus lens to anode gap, the extractor to focus spacing, and the specific lens geometries were found by minimization of the resulting gun magnification and chromatic and spherical aberrations. This optimized gun has a focus lens to anode spacing of 60 mm and an extractor to focus lens spacing of 3 mm. At 100 kV, the beam spot size is predicted to be dominated by chromatic aberration. The image side spherical and chromatic aberration coefficients, are 39 700 and 4710 mm, respectively. For a gun magnification of 1.15, the contributors to beam size are chromatic: 395 Å; spherical: 20 Å; diffraction: 111 Å; and the Gaussian source: 230 Å, yielding a quadrature sum spot size of 417 Å for extraction voltage, acceptance angle, and energy spread of 5 kV, 2.2 mrad, and 2.0 eV, respectively.

VI. TEST RESULTS

A graphite Faraday cup was used to measure the beam current of the 0.7-μm tip radius Schottky emitter operated at 1825 K with -300 V of suppressor voltage. The beam current drift for 0.5-mA/sr operation was $<0.5\%$ per hour. Figure 3 shows the gun image distance vs the focus voltage at 100 kV beam energy for a variety of extraction voltages. Most of the positive sloping section of the curve corresponds to a deceleration mode while the negative sloping branch corresponds to an acceleration mode. The focus lens voltages of 5084 and 6548 V for image distances of 145 and 245 mm, respectively, are in reasonable agreement with the predicted values.

The beam spot size was measured as a 15% to 85% rise time across a GaAs edge. The rise time measurement provides only an upper bound on the beam size. Both reflected and transmitted signals were monitored and found to be within general agreement. Figure 4 shows the beam crossover diameter vs acceleration potential data for acceleration potentials of 25, 50, 75, and 100 kV. The solid line in Fig. 4 is

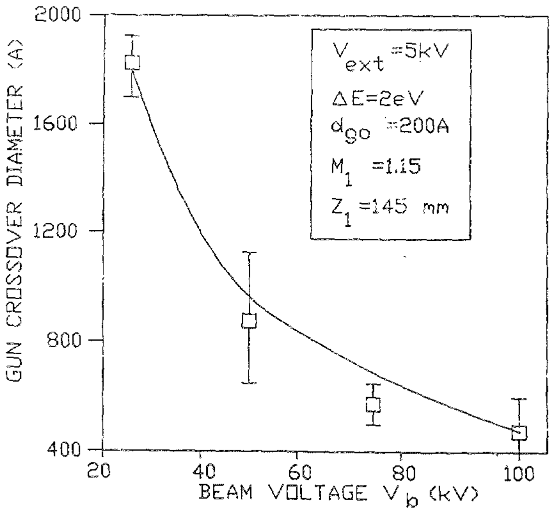

FIG. 4. Gun crossover diameter vs beam voltage. The solid line represents the computer results where the boxes indicate the average experimental values.

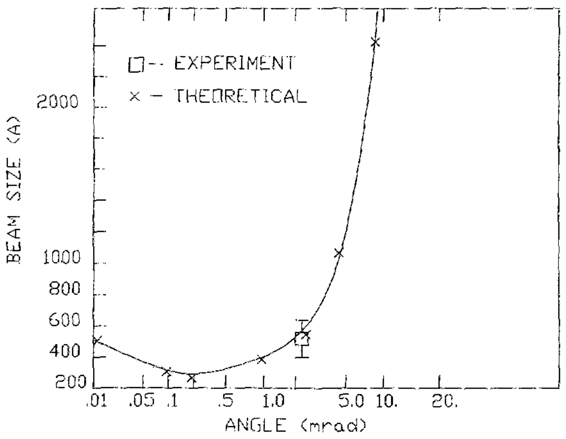

FIG. 5. 100 kV beam diameter vs gun acceptance angle. The solid line represents the computed relationship based on geometrical optics by the quadrature sum method. The data point indicates the beam diameter measured from an acceptance aperture of 2.2 mrad.

the computer result assuming an energy spread of 2 eV. At 100 kV there is good agreement between the average experimental and computer results of beam diameters of 46 and 47 nm, respectively. At 25 kV, the average experimental and computer beam crossover diameters are 184 and 179 nm, respectively. The decrease in beam crossover diameter with increasing acceleration energy results from the reduction in both the chromatic aberration contribution and the magnification. Figure 5 shows the quadrature sum calculated beam crossover diameter at 100 kV using the parameters of Fig. 4. The residual beam size at the minimum is due to the virtual source size. The steep increase in the beam size for large acceptance angles results primarily from the spherical contribution.

Ambient vibration in the beam was estimated by averaging the time shift of the GaAs knife edge rise time signal. The worst case estimate for the ambient vibration induced beam size blur is about 7 nm. When this gun is used with a magnetic objective lens with a column demagnification of 7, the effects of vibration will be significantly reduced.

VII. CONCLUSION

A 100 kV electrostatically focused SE electron gun was designed and built. The design features include a modular source/optic unit, a replaceable beam limiting aperture, and an adjustable ground electrode for alignment. We have operated the gun from below 25 to 100 kV and achieved reasonable agreement with the theoretical values. The gun, when used in conjunction with a 10× demagnification projection lens, is expected to deliver a final spot size between 6 and 8 nm. One application for this gun is to expose x-ray mask membranes for high resolution 1× masks.

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