SAPHIRE (scintillator avalanche photoconductor with high resolution emitter readout) for low dose x-ray imaging: Spatial resolution

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An indirect flat panel imager (FPI) with programmable avalanche gain and field emitter array (FEA) readout is being investigated for low-dose and high resolution x-ray imaging. It is made by optically coupling a structured x-ray scintillator, e.g., thallium (Tl) doped cesium iodide (CsI), to an amorphous selenium (*a*-Se) avalanche photoconductor called high-gain avalanche rushing amorphous photoconductor (HARP). The charge image created by the scintillator/HARP (SHARP) combination is read out by the electron beams emitted from the FEA. The proposed detector is called scintillator avalanche photoconductor with high resolution emitter readout (SAPHIRE). The programmable avalanche gain of HARP can improve the low dose performance of indirect FPI while the FEA can be made with pixel sizes down to 50 μm . Because of the avalanche gain, a high resolution type of CsI (Tl), which has not been widely used in indirect FPI due to its lower light output, can be used to improve the high spatial frequency performance. The purpose of the present article is to investigate the factors affecting the spatial resolution of SAPHIRE. Since the resolution performance of the SHARP combination has been well studied, the focus of the present work is on the inherent resolution of the FEA readout method. The lateral spread of the electron beam emitted from a 50 $\mu\text{m} \times 50 \mu\text{m}$ pixel FEA was investigated with two different electron-optical designs: mesh-electrode-only and electrostatic focusing. Our results showed that electrostatic focusing can limit the lateral spread of electron beams to within the pixel size of down to 50 μm . Since electrostatic focusing is essentially independent of signal intensity, it will provide excellent spatial uniformity. © 2008 American Association of Physicists in Medicine. [DOI: 10.1118/1.2937652]

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I. INTRODUCTION

Existing active matrix flat-panel imagers (AMFPI) use a two-dimensional array of thin film transistors (TFT) to read out a charge image generated by an x-ray image sensor, either an x-ray photoconductor or a scintillator coupled with discrete photodiodes for the direct and indirect conversion methods, respectively. While AMFPI provides better image quality than traditional screen films and computed radiography,^{1,2} its imaging performance has not yet reached the optimum. Further improvements, especially in spatial resolution and low dose performance, are desirable. Existing AMFPIs have two main limitations: (1) the electronic noise degrades the imaging performance behind dense tissues in low dose application. It has been shown that the detective quantum efficiency (DQE) of mammography AMFPIs at ~ 1 mR can be less than 50% of that at 10 mR,³ i.e., the detector is not x-ray quantum noise limited. This problem will be worse with a decrease in pixel size or x-ray dose, such as that used in breast tomosynthesis. (2) The pixel size currently used in mammography AMFPI ranges from 70 to 100 μm . With further decrease in pixel size, the fill factor decreases, resulting in DQE degradation due to noise aliasing (direct FPI) and deleterious effect of electronic noise (both direct and indirect FPI).^{4,5} On the other hand, a smaller pixel size may be desirable from a clinical point of view. There is

still an ongoing debate on what pixel size is optimal for the detection of calcifications. Studies have shown that d_{e1} smaller than 100 μm provides better detection and characterization of calcifications.^{6,7} Therefore, detector technologies capable of smaller pixel size without compromise in DQE is highly valuable for exploring the optimal pixel size for mammography.

To improve the detector low dose performance with high resolution, we propose a new concept of indirect conversion flat-panel imager with avalanche gain and field emitter array (FEA) readout, which is referred to as scintillator avalanche photoconductor with high resolution emitter readout (SAPHIRE). The concept of SAPHIRE is shown with the schematic drawing in Fig. 1. It consists of a thallium (Tl) doped needle-structured cesium iodide (CsI) scintillator optically coupled (e.g., through fiber optics) to a uniform thin layer (4–25 μm) of avalanche amorphous selenium (*a*-Se) photoconductor called high-gain avalanche rushing amorphous photoconductor (HARP). The optical photons emitted from the scintillator transmit through a transparent indium tin oxide (ITO) bias electrode of HARP and generate electron-hole pairs near the top interface of the HARP layer. By applying a positive voltage to the ITO electrode through a resistor, holes move toward the bottom (free) surface of the HARP and experience avalanche multiplication under an

FIG. 1. Schematics showing the concept of the proposed detector SAPHIRE: cross-sectional view showing the operating principles.

electric field strength of $E_{Se} > 70 \text{ V}/\mu\text{m}$,^{8,9} which is an order of magnitude higher than that typically used in direct *a*-Se x-ray detector. The holes form an amplified charge image at the bottom surface of HARP and are readout with the electron beams generated by a two-dimensional FEA, which is placed at a short distance, e.g., 1 mm, below the scintillator-HARP (SHARP) structure. A mesh electrode, biased with positive potential, is inserted halfway between the FEA and HARP target to minimize the lateral spread of electron beams before they land on the free surface of the HARP target. The amount of charge required to return the bottom surface of the HARP target to ground (cathode) potential is measured by an amplifier connected (through alternating current coupling) to the ITO electrode to form the output signal.

The concept of electron beam readout is similar to that used in optical and x-ray vidicons,¹⁰ except that the FEA is a compact, two-dimensional source of electron beams, allowing the construction of the detector in the form of a FPI. As an emerging technology for large area flat-panel field emission displays (FEDs),¹¹ FEA has the potential to provide a smaller pixel size than that achieved with the TFT readout. The field emitter (FE) tips (with spacing of $\sim 1 \mu\text{m}$) are connected to base electrodes arranged in columns, and rows of gate electrode are used to control the field emission. The overlapping area between the base and gate electrodes defines the pixel size, and sufficient FE tips can be included in $d_{el}=50 \mu\text{m}$ to provide sufficient emission current to produce the wide dynamic range required in medical images. Each pixel is addressed by applying a forward bias between the gate and the base. This driving scheme is very similar to that used in passive matrix liquid crystal displays. The main disadvantage of the passive driving scheme is the pulse delay due to load resistance and capacitance of each line. To alleviate this problem, active matrix FEA has recently been developed,^{12,13} where each pixel is addressed through a transistor.

Compared to existing AMFPI, SAPHIRE has the following advantages: (1) Programmable avalanche gain g_{av} ensures a wide dynamic range. By increasing the electric field E_{Se} , high g_{av} can be applied at low dose applications (e.g.,

fluoroscopy or tomosynthesis) to achieve x-ray quantum noise limited performance, while g_{av} is turned off at high dose (e.g., radiography).¹⁴ At each g_{av} setting, the signal first increases linearly as a function of radiation exposure. As the exposure exceeds the range that the g_{av} is selected for, the image charge accumulated on the bottom free surface lowers the potential drop across the HARP layer, and causes g_{av} to gradually decrease.¹⁵ This ensures that HARP continues to respond to radiation without complete saturation, resulting in a wide dynamic range. (2) FEA may provide smaller pixel size than is possible with TFTs. (3) A high resolution (HR) type of CsI can be used because of the additional gain provided by HARP. HR type CsI has less Lubberts effect, i.e., depth dependent blur, which is the main source of DQE degradation at high spatial frequencies.^{16,17} Despite its resolution advantages, HR CsI has not been used widely in commercial indirect FPI due to its lower conversion gain, which makes the detector more susceptible to electronic noise at low exposure levels.^{5,18}

In this present article, we focus our investigation on the factors affecting the spatial resolution of SAPHIRE. Since breast imaging is the application that requires the highest spatial resolution, we will use a hypothetical mammography detector design as an example for our discussion, although SAPHIRE can be used in a general purpose R/F detector as well. In Sec. II, we provide a brief review of the principles of field emission and the electron beam readout method, especially the parallel electron beam readout proposed for SAPHIRE. In Sec. III we present our theoretical and simulation methods for investigating the spatial resolution of SAPHIRE, focusing on the factors related to the FEA readout. Two different electron-optical designs for focusing the electron beams are included in our investigation: (1) a basic design incorporating only a mesh electrode, such as that shown in Fig. 1, and (2) electrostatic focusing in addition to the mesh electrode. In Sec. IV, the results for different electron-optical designs are presented and compared from which we draw conclusions about the desired methods for electron beam focusing in SAPHIRE. The properties of lag and noise are also under investigation, they will be submitted in a separate article.

II. THEORY AND BACKGROUND

The FEA is a practical vacuum microelectronic device built to nanometer tolerance. Several technologies have been invented for manufacturing FEA for flat-panel display applications. They include surface-conduction electron emitter,¹⁹ carbon nanotube,²⁰ metal-insulator-metal emitter as ballistic electron surface emitting device,^{21,22} metal-insulator-semiconductor in high-efficiency electron emission devices,²³ and Spindt-type field emitters.²⁴ The characteristics of different FEA technologies vary in the angular distribution and intensity of the emitted electron beams. In FED, the anode (phosphor) is usually biased with a positive potential at tens of thousands of volts, which accelerate the electrons to high speed and minimize the time the electrons take to reach the anode. As a result, the lateral spread of the

electron beam, which is due to the lateral velocity component of the electrons emitted with an oblique angle, is negligible compared to the pixel size. However, in an image sensor, the potential on the bottom surface of the photoconductive target is proportional to the image signal and is typically less than a few tens of volts. Therefore, additional electron-optical focusing methods need to be developed to ensure that the electrons can reach the target without considerable lateral spread. Furthermore, the intensity of the electron beam has to be sufficient for reading out the highest signal current generated in the HARP target.

Compared to the other types of FEA, Spindt-type field emitters have higher emission intensity and narrower angular distribution. They have also proven to be robust and stable over time.²⁵ Prototype Spindt-type FEDs with diagonal dimensions of 20.3 and 28.7 cm have been presented,^{26,27} which are approaching the imager size required for medical FPI. For the remainder of this article, we will use the typical characteristics of Spindt-type FEA as an example for our investigation. The most commonly used material for the Spindt-type FE tips is molybdenum (Mo). The FEA is enclosed in high vacuum (10^{-9} Torr) during operation. To turn on field emission, the cone-shaped Mo cathode is biased at ground potential and a positive bias, V_g (40–100 V), is applied to the gate electrode. This bias condition results in a very high E_{FE} around the emitter tip due to its small hemispherical radius of 300 Å (Refs. 24 and 25) and causes field emission. Each pixel consists of a matrix of FE tips and different pixels of a FEA are addressed by orthogonal base and gate lines, i.e., a passive driving scheme. A prototype FEA with $d_{el}=50\text{ }\mu\text{m}$ with 17×17 tips in each image pixel has been used in a 1 in. diameter optical HARP FEA image sensor.²⁸

The size of the FPI required for x-ray imaging is much larger than that for optical imaging, e.g., $20\text{ cm}\times 25\text{ cm}$ for mammography. A pixel size of $50\text{ }\mu\text{m}$ would result in 4000×5000 pixels. This necessitates division of the ITO signal/bias electrode into multiple strips for two reasons: (1) One large ITO electrode would result in a large input load capacitance for the amplifier, which leads to increased electronic noise; (2) The large passive load (capacitance and resistance) of each gate and base line of a large area FEA results in driving pulse delay, which requires that each pixel be turned on for at least $0.16\text{ }\mu\text{s}$. A FEA matrix of 4000×5000 pixels would require 3.2 s to read out pixel-by-pixel. If the ITO electrode is divided into N_s stripes and each connected to a charge amplifier, as shown in Fig. 2, N_s pixels can be turned on simultaneously for parallel readout and increase the readout speed by N_s times. The major benefits of parallel beam readout are the decrease in readout lag and noise, which will be discussed in separate publications. For the discussion in the present article, the parallel beam readout only has an impact on the pixel turn on time (t_p), which affects the pixel aperture function (to be discussed in Secs. III C and IV C).

FIG. 2. 3D schematic view of the parallel beam readout method to show the simultaneous emission of electron beams from several pixels of the FEA, one for each ITO strip. The mesh electrode and CsI are removed from the SAPHIRE structure for clarity of illustration.

III. METHODS

There are several factors affecting the spatial resolution of SAPHIRE: (1) the inherent resolution of the optically coupled SHARP combination; (2) the FEA pixel size; and (3) the lateral spread of the electron beams. The first factor is dominated by the blur in the structured CsI scintillator, since the photon detection and avalanche process in HARP has been shown to have no blur in high definition optical HARP camera that operates with an effective pixel size of $10-20\text{ }\mu\text{m}$.^{29,30} The spatial resolution properties of CsI has been investigated previously^{14,16,31} and the results for a $150\text{ }\mu\text{m}$ thick HR type CsI will be used here in comparison with the other factors. This measured presampling MTF included the inherent image blur of the columnar CsI and the optical properties of the fiber optic faceplate, on which the CsI was deposited. Since the diameters of the CsI columns and the optical fiber are $5-10\text{ }\mu\text{m}$, their effects (aperture function and sampling) on the MTF are negligible, and the measured MTF is regarded shift invariant. In this section, we will describe the methods for investigating the lateral spread of electrons emitted from the FEA and its effect on the aperture function of the readout method.

III.A. Lateral spread of electron beam in FEA readout

The geometric arrangement of FE tips on each pixel of the FEA determines the area of emission. However, the spatial resolution of the FEA readout is determined by the lateral extent and intensity of the electron beam when it reaches the bottom surface of the HARP target. As shown in Fig. 3, the electrons emitted from each FE tip have a finite angular range of up to $40^\circ-50^\circ$.³² The lateral travel distance of an electron is equal to the integration of the lateral component of its velocity v_x over the time t_{gt} it takes to travel from the gate electrode to the target. Since the value of V_t on the bottom surface of HARP due to x-ray exposure is on the order of several volts, it is necessary to insert a mesh electrode with potential V_m of several hundred volts between the

FIG. 3. Schematic diagram showing the lateral spread of electron beams emitted from the FEA.

HARP target and the FEA. As shown in Fig. 3, the mesh electrode will accelerate the axial velocity component (v_z) of the electrons thus shorten t_{gt} . After the electrons transmit through the mesh electrode, they decelerate due to the reversed electric field, and only those electrons with sufficient initial value of v_z can reach the target. The other electrons decelerate to $v_z=0$ before reaching the target, and return to the mesh electrode.

To reduce the lateral spread of electrons, different electron-optical focusing designs have been investigated to reduce either v_x or t_{gt} . In this article two different electron-optical designs were investigated: (1) mesh-electrode-only and (2) electrostatic focusing in addition to the mesh electrode. Beside these two designs, a magnetic focusing design has been implemented for a 1 in. HARP-FEA sensor.²⁸ However, due to the difficulty in maintaining a uniform magnetic field over a large area, it may not be practical for SAPHIRE and will be not discussed in this article. For each electron-optical design, we used a two-step approach to determine the lateral extent and intensity of electron beams: (1) determine the lateral travel distance of a single electron emitted from a single FE tip; and (2) compute the spread and intensity of the electron beam emitted from one pixel of the FEA, which includes a two-dimensional array of tips. These two steps will be described in this subsection (Sec. III A) and the next subsection (Sec. III B), respectively.

III.A.1. Mesh-electrode-only

As described above, the simplest method to reduce t_{gt} , and hence, lateral spread is to insert a mesh electrode halfway between the HARP target and the FEA, as shown in Fig. 3. If we assume that all electrons have the same initial energy $E = qV_g$ after emission from the gate electrode, the lateral spread can be derived analytically as shown in the Appendix and is given by³³

FIG. 4. Cross-sectional view showing the structure of a double-gated Spindt-type emitter with focusing electrodes, which deflect the electrons with large emission angle to axial direction.

$$LS = 2\sqrt{V_g} \sin \theta \cdot L_{gm} \left(\frac{\sqrt{V_m - V_g \sin^2 \theta} - \sqrt{V_g} \cos \theta}{V_m - V_g} \right) + 2\sqrt{V_g} \sin \theta \cdot L_{mt} \left(\frac{\sqrt{V_m - V_g \sin^2 \theta} - \sqrt{V_t - V_g \sin^2 \theta}}{V_m - V_t} \right), \quad (1)$$

where L_{gm} and L_{mt} are the gate-mesh and mesh-target distances, respectively. Only the electrons with smaller θ , and hence, higher initial v_z can reach the target. So there exists a critical emission angle θ_c , within which the emitted electrons can reach the target. θ_c is determined by V_t and V_g of the FEA,³³

$$\theta_c = \arcsin \left(\sqrt{\frac{V_t}{V_g}} \right). \quad (2)$$

The maximum value of lateral spread LS_{max} occurs with critical angle θ_c and can be obtained by substituting θ in Eq. (1) with θ_c in Eq. (2),

$$LS_{max} = 2\sqrt{V_t} \cdot L_{gm} \left(\frac{\sqrt{V_m - V_t} - \sqrt{V_g - V_t}}{V_m - V_g} \right) + 2\sqrt{V_t} \cdot L_{mt} \left(\frac{1}{\sqrt{V_m - V_t}} \right). \quad (3)$$

Equation (3) shows that LS_{max} depends on the geometry and the operating conditions of the SAPHIRE, e.g., L_{gm} , L_{mt} , V_m , and V_g , as well as on the x-ray exposure (i.e., V_t).

III.A.2. Electrostatic focusing

Electrostatic focusing is feasible for large area SAPHIRE. The concept of electrostatic focusing proposed for SAPHIRE is shown in Fig. 4. An additional (focusing) electrode is added on top of the gate electrode for each FE tip, and this structure was referred to as the double-gated Spindt-type emitter.²⁵ Both electrodes are made of Mo through photolithography and are separated by an insulating layer (e.g., SiO_2). To deflect the electrons emitted with large θ back to the axial direction, a focusing electrode potential V_L that is

much lower than gate potential V_g is applied. The choice of V_L depends on the geometry of the double-gated tip.

The lateral spread of electrons with electrostatic focusing cannot be determined analytically. Instead, the electron trajectory was simulated using the finite element method (FEM). A commercial FEM simulation software (COMSOL Multiphysics®) was used to solve for the electric field distribution between the HARP target and the FEA. Since the size of each FE tip ($\sim 1 \mu\text{m}$) is three orders of magnitude smaller than the distance between the target and the gate L_{gt} ($\sim 1 \text{ mm}$), variable resolution was used to set up the finite element mesh in the simulation. The element size chosen for the vicinity of the FE tip was $\sim 1 \text{ nm}$ to ensure accurate simulation of electron trajectory with the focusing electrode. Since the structure of each FE tip was identical and independent, the simulation was performed on a single FE tip with circular symmetry around the tip. With axial distance of $> 2 \mu\text{m}$ above the focusing electrode, the electric field becomes essentially parallel; therefore, the element size for simulation was increased gradually to $\sim 1 \mu\text{m}$ to minimize the simulation time. The trajectories of a single electron emitted at different angles were determined with separate runs of the simulation.

III.B. Spatial distribution of electron beam intensity

The spatial distribution of the electron beam intensity as it reaches the HARP target, $I(x, y)$, was calculated for each pixel of the FEA with $d_{\text{el}} = 50 \mu\text{m} \times 50 \mu\text{m}$. This pixel design has been developed for a prototype 1 in. optical HARP-FEA sensor,²⁸ in which an array of 17×17 FE tips was evenly distributed in an emission area of $20 \mu\text{m} \times 20 \mu\text{m}$ in the center of each pixel.

The electron beam intensity from a single tip, $I_0(x, y)$, was first obtained by substituting the inverse of the relationship between lateral spread and θ in Sec. III A, i.e., $\theta = \text{LS}^{-1}(x, y)$, into the angular intensity distribution of field emission, $I_\theta(\theta)$, from a single tip, and then converting the result to Cartesian coordinates

$$I_0(x, y) = I_\theta[\text{LS}^{-1}(x, y)]. \quad (4)$$

The distribution of $I_\theta(\theta)$ used in our calculation is shown in Fig. 5 and was adapted from the simulation and experimental measurements by Itoh *et al.* for Spindt-type FEA.³² The beam intensity for one pixel was then calculated by integrating $I_0(x, y)$ over all the FE tips in the x and y directions with $N_x = N_y = 17$,

$$I(x, y) = \sum_{N_x} \sum_{N_y} I_0(x - n_x d_t, y - n_y d_t). \quad (5)$$

The method described above assumes that the interaction between electrons emitted from the same tip or neighboring tips is negligible. The main mechanism for interaction between electrons is the space charge effect due to the electric field generated by other electrons. This effect is proportional to the electron beam intensity and the square of the electron travel time t_{gt} and inversely proportional to the radius of the electron beam. The space charge effect for the electron beam

FIG. 5. Angular distribution of electrons in Spindt-type field emitters, adapted from Ref. 32.

in a Vidicon has been investigated previously.³⁴ It was found that for a distance of 2 cm between the last focusing (mesh) electrode and the target, the additional spread of electron beam due to the space charge effect was $11 \mu\text{m}$ with a beam current of $1.6 \mu\text{A}$ and radius of $166 \mu\text{m}$ at the mesh electrode. For FEA readout with a similar beam current ($2 \mu\text{A}/\text{pixel}$), the additional spread due to the space charge effect is expected to be $< 1 \mu\text{m}$ because the travel distance L_{gt} is only 1 mm, which results in a travel time ($\sim 0.18 \text{ ns}$) that is more than an order of magnitude smaller than that in the Vidicon ($\sim 2.13 \text{ ns}$).³⁴ Therefore, this effect can be ignored in our calculation of lateral spread of electron beams.

III.C. Pixel aperture function

The pixel aperture function of the FEA readout method, $\text{MTF}_{\text{FEA}}(f_x, f_y)$, was determined from the Fourier transform of the spatial distribution of the image charge on the target, $Q_a(x, y)$, that was read out by each FEA pixel. $Q_a(x, y)$ is given by the integral of $I(x, y)$ within the pixel readout time t_p ,

$$Q_a(x, y) = \int_0^{t_p} I(x, y) dt. \quad (6)$$

During electron beam readout, the target potential V_t decreases with time as the electrons reach the target. Since $I(x, y)$ is V_t dependent, $Q_a(x, y)$ was calculated numerically by dividing t_p into small steps and updating $I(x, y)$ in real time. After $Q_a(x, y)$ was calculated for each focusing method, $\text{MTF}_{\text{FEA}}(f_x, f_y)$ was obtained through two-dimensional Fourier transform

$$\text{MTF}_{\text{FEA}}(f_x, f_y) = \frac{|\text{FT}[Q_a(x, y)]|}{\text{MTF}_{\text{FEA}}(0, 0)}. \quad (7)$$

TABLE I. Detector geometry and bias conditions used for all two electron-optical designs.

V_g (V)	V_m (V)	L_{gm} (mm)	L_{mt} (mm)
40	350	0.5	0.5

he presampling MTF of SAPHIRE was then calculated by multiplying the $MTF_{FEA}(f_x, f_y)$ by the MTF of the SHARP combination

$$MTF_{SAPHIRE} = MTF_{SHARP} \times MTF_{FEA}. \quad (8)$$

IV. RESULTS AND DISCUSSION

IV.A. Lateral spread of electron beam in FEA readout

IV.A.1. Mesh-electrode-only

The trajectory of electrons emitted with angle θ was determined using Eqs. (A5) and (A6) in the Appendix, and the corresponding lateral spread was calculated using Eq. (1). The detector geometry and bias conditions used in the calculation, i.e., V_g , V_m , L_{gm} , and L_{mt} are listed in Table I. Shown in Fig. 6 is the trajectory of electrons emitted with the critical angle $\theta_c = 5.74^\circ$. The lateral distance traveled by the electron when it reaches the target corresponds to the maximum lateral spread, which is $59 \mu\text{m}$ at $V_t = 0.4 \text{ V}$. Since electrons emitted with $\theta > 5.74^\circ$ return to the mesh electrons, only a small fraction of the electron beam is utilized for readout. The efficiency increases with higher V_t because electrons with larger emission angle can reach the target. However, the drawback is a larger lateral spread, which increases to $444 \mu\text{m}$ with $V_t = 20 \text{ V}$. The major limitation of the mesh-electrode-only design is that lateral spread varies as a function of signal, which will lead to image artifact due to non-uniformity in spatial resolution that cannot be easily corrected. Furthermore, while this magnitude of lateral

spread may be acceptable for general radiographic applications with pixel size ranging from $d_{el} = 150\text{--}200 \mu\text{m}$, it is not adequate for mammography with $d_{el} = 50\text{--}100 \mu\text{m}$. As shown in Eq. (1), lateral spread can be reduced by increasing V_m or decreasing L_{gt} , however, this makes the detector much more difficult to manufacture. Therefore, for mammography, additional focusing without reduction in L_{gt} is desirable.

IV.A.2. Electrostatic focusing

The electron trajectory for electrostatic focusing was obtained using finite element method. The result for the same emission angle of $\theta = 5.74^\circ$ is shown in Fig. 6 in comparison with the mesh-electrode-only design. It shows that electrostatic focusing can reduce substantially the lateral spread (from 59 to $6 \mu\text{m}$). Next we will further examine the dependence of electrostatic focusing on different FEA operating conditions.

IV.A.2.a. Electrostatic focusing electrode potential V_L

With electrostatic focusing, the major factor affecting the trajectory of emitted electrons is the bias potential V_L on the electrostatic focusing electrode. In general, $V_L < V_g$ is required to produce the focusing effect. Since the focusing electrode is located $< 1 \mu\text{m}$ away from the gate, V_L has to be chosen carefully to avoid inadequate focusing. The diagrams in Fig. 7 show qualitatively the effect of V_L on the trajectory of electrons emitted from different angles. Our strategy in the choice of V_L is to minimize underfocusing, which leads to larger lateral spread and loss of electrons. Our simulation of electron trajectories with different V_L showed that $V_L = -2 \text{ V}$ provides the best compromise, and this value was used for calculating the results in Fig. 8.

Shown in Fig. 8 is the lateral spread as a function of θ for the operating conditions in Table I and FE tip geometry in Fig. 4. The $LS_{\max}$ occurs at $\theta = 20^\circ$. This is because electrons emitted with larger θ are deflected by the focusing electrode and result in lower lateral spread. Electrons emitted with $\theta > 28^\circ$ are absorbed by the focusing electrodes in this simulation setting.

To facilitate the calculation of the pixel aperture function in the next section, the relationship between lateral spread and θ shown in Fig. 8 was fitted with a sixth order polynomial function, and the fitting result is shown for comparison in the same graph.

IV.A.2.b. HARP target free surface potential V_t In the mesh-electrode-only design, the lateral spread increases substantially with V_t (larger than the desired pixel size) and would result in nonuniformity in spatial resolution. Figure 9 shows the results of lateral spread with electrostatic focusing as a function of V_t for two emission angles: $\theta = 5^\circ$ and 20° . The figure shows that lateral spread decreases as V_t increases due to the reduction in electron travel time t_{gt} . However, the variation in lateral spread is $< 2 \mu\text{m}$ over a V_t range of $0\text{--}30 \text{ V}$. Since this variation is much smaller than the desired pixel size, lateral spread can be regarded as essentially independent of V_t , which leads to uniform spatial resolution across the image.

FIG. 6. Trajectories of electrons after emission from the FEA and before reaching the HARP target for both electron-optical designs. The mesh electrode is placed half-way between the FEA and the target, which are separated by 1 mm . The detector geometry and bias conditions used for the calculation are shown in Table I.

FIG. 7. Conceptual electron trajectories under different V_L bias conditions. (a) For electrons emitted with the same angle, different V_L results in different lateral spread. (b) For the same V_L , electrons emitted with different angle results in different lateral spread.

Another difference for electrostatic focusing is that the fraction of emitted electrons utilized for readout is essentially independent of V_t because all electrons emitted with $\theta < 28^\circ$ can reach the target and contribute to the readout. Whereas with the mesh-electrode-only design, the critical angle θ_c decreases with decreasing V_t , as indicated by Eq. (2), which means that the readout becomes less efficient as V_t approaches ground (cathode) potential.

IV.A.2.c. Detector geometry and bias conditions: V_m and L_{gt} The dependence of lateral spread on V_m is shown in Fig. 10 for $\theta = 5^\circ$ and 20° . Plotted in the same graph for comparison is the lateral spread versus V_m for mesh-electrode-only design calculated using Eq. (3). It shows that lateral spread decreases with increase in V_m . This is because the lateral spread is the product of v_x and t_{gt} in both designs. While v_x is reduced substantially by the focusing electrode,

t_{gt} can be reduced by increasing V_m or decreasing L_{gt} . However, since the lateral spread is much lower than that in mesh-electrode-only design, electrostatic focusing is much more tolerant to changes in detector geometry.

IV.B. Spatial distribution of electron beam intensity

The intensity of the electron beam reaching the target from a single tip, $I_0(x, y)$ was obtained using Eq. (4). The angular dependence of lateral spread required for Eq. (4) was established using Eq. (1) and Fig. 8 for the two electron-optical designs, respectively. The results of the $I_0(x, y)$ calculation are shown in Fig. 11. Since $I_0(x, y)$ has circular symmetry, the results are shown as a function of x only (with $y = 0$).

FIG. 8. Lateral spread of electrons with electrostatic focusing design as a function of electron emission angle θ under the operating conditions in Table I and FE tip geometry in Fig. 4. The target potential $V_t = 0.6$ V.

FIG. 9. Lateral spread of electrons with electrostatic focusing as function of target potential V_t for electrons emitted at $\theta = 5^\circ$ and 20° .

FIG. 10. Lateral spread of electron beams with the electrostatic focusing as a function of mesh electrode potential V_m with $V_t=1.5$ V. For comparison, the result for mesh-electrode-only at $V_t=0.4$ V is plotted in the same graph.

As shown in Fig. 11, $I_0(x,y)$ for the mesh-electrode-only design has a lower intensity and wider spread; and it is not suitable for mammography detectors. For electrostatic focusing, $I_0(x,y)$ is the lowest near the center and peaks at the edge. The low intensity at the center is because electrons emitted with small θ are not affected substantially by the focusing electrode and their trajectory is similar to that in the mesh-electrode-only design. However, near the edge, where lateral spread is in the range of 26–27 μm , electrons emitted with a much wider angular range accumulate due to the effect of electrostatic focusing. This can be seen from the lateral spread versus θ graph in Fig. 8, where the curve is essentially flat near the maximum lateral spread of 27 μm for θ between 16° and 23°.

The results of $I_0(x,y)$ shown in Fig. 11 were used to calculate $I(x,y)$ for the entire pixel with 17×17 FE tips. The

FIG. 11. Comparison of the electron beam intensity on target for a single FE tip, $I_0(x,y)$, for the two electron-optical designs.

FIG. 12. Electron beam intensity distribution $I(x,y)$ for each pixel of the FEA with electrostatic focusing design. The boundary of each graph measures 100 $\mu\text{m} \times 100 \mu\text{m}$, the outer square represents the pixel size of 50 $\mu\text{m} \times 50 \mu\text{m}$; and the small square in the center outlines the emitting area of 20 $\mu\text{m} \times 20 \mu\text{m}$.

intensity distribution of $I(x,y)$ is shown in gray scale in Fig. 12 for electrostatic focusing. The result for mesh-electron-only design is not shown because the electron beam extends far beyond the pixel size of 50 μm and is not suitable for high resolution imaging applications such as mammography. In Fig. 12, the black square in the center outlines the emitting area of 20 $\mu\text{m} \times 20 \mu\text{m}$, the outer square represents the desired $d_{\text{el}}=50 \mu\text{m}$, and the boundary of 100 $\mu\text{m} \times 100 \mu\text{m}$ shows the extent of electron beam spreading. Figure 12 shows that the intensity in the center of the pixel is the lowest, which is resulted from the shape of $I_0(x,y)$ shown in Fig. 11.

IV.C. Pixel aperture function

The spatial distribution of the image charge on the HARP target that is read out by each FEA pixel, $Q_a(x,y)$, was obtained using Eq. (6). Besides the parameters list in Table I, the pixel readout time t_p and the initial target potential V_t also affect $Q_a(x,y)$. In breast tomosynthesis, which is an emerging three-dimensional (3D) imaging technique using digital mammography detectors, a readout rate of 2–6 frames/s is required. This translates to $t_p=1-3 \mu\text{s}$ if we divide the ITO electrode of SAPHIRE into $N_s=128$ strips. For simplicity of analysis, $V_t=20$ V was chosen for the calculation of $Q_a(x,y)$. This target potential corresponds to a detector exposure of 7 mR for tomosynthesis, which is 3.5 times the mean exposure.¹⁷ For screening mammography, $V_t=20$ V corresponds to the mean detector exposure of 20 mR. The result of $Q_a(x,y)$ calculation for electrostatic focusing is shown in Fig. 13. Since $Q_a(x,y)$ has circular symme-

FIG. 13. The spatial distribution of image charge on target, $Q_a(x, y=0)$, that is read out by each FEA pixel. The initial $V_i=20$ V.

try, the result is plotted as a function of x only (with $y=0$). It shows that the shape of Q_a for electrostatic focusing is essentially flat across the pixel, despite the lower $I(x, y)$ intensity at the center. This is because the absolute values of $I(x, y)$ are sufficient to read out 100% of the image charge within t_p of 3 μ s.

The pixel aperture function for electrostatic focusing, MTF_{FEA_E} , was then derived from the Fourier transform of $Q_a(x, y)$ using Eq. (7) and the result is shown in Fig. 14. At 5 cycles/mm, the value of MTF_{FEA_E} is 84%. At 10 cycles/mm, which is the Nyquist frequency for $d_{el}=50$ μ m, the value decreases to 46%. For comparison, the inherent MTF for SHARP (MTF_{SHARP}) and the total detector MTF (MTF_{system}) are also shown in Fig. 14. The values used for MTF_{SHARP} were adapted from our previous investigation

FIG. 14. The presampling MTF calculated from $Q_a(x, y)$ in Fig. 13 for the FEA readout method with electrostatic focusing (denoted as _E) methods. The presampling MTF for SHARP combination and the resulting system MTF for SAPHIRE are shown in the same graph.

of 150 μ m thick HR type CsI layers.¹⁶ Figure 14 shows that the inherent resolution of SHARP is the dominant source of blur in SAPHIRE.

V. CONCLUSIONS

A new detector concept SAPHIRE is being investigated to improve the low dose x-ray imaging performance of indirect FPI. In this article, we investigated the spatial resolution aspect of the imaging performance of SAPHIRE. The lateral spread of the electron beam emitted from the FEA, and the resulting pixel aperture function of the FEA readout method was investigated for two different electron-optical designs: mesh-electrode-only and electrostatic focusing. It was found that electrostatic focusing provides a pixel aperture function that is independent of the x-ray signal. It also provides a higher beam current by allowing more emitted electrons to reach the target. Therefore, it is the most promising electron-optical focusing method to be incorporated in the design of SAPHIRE for high resolution, low-dose x-ray imaging applications.

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APPENDIX: DERIVATION OF ELECTRON TRAJECTORY AND LATERAL SPREAD FOR MESH-ELECTRODE-ONLY DESIGN

In this appendix, the trajectory of the electrons and the resulting lateral spread is derived for the mesh-electrode-only design. The lateral spread is the product of the lateral component of the electron velocity, v_x , and the time it takes the electron to travel from the gate to the HARP target, t_{gt} . The electrons were assumed to have an initial kinetic energy of $KE_0=qV_g$ after emission from the gate electrode with an angle of θ (respect to z axis), hence, v_x is given by

$$v_x = \sqrt{\frac{2qV_g}{m}} \sin \theta, \quad (A1)$$

where m is the mass of an electron. Since the electric field is in the z direction, v_x remains unchanged as the electrons travel to the target. The potential $V(z)$ and the axial velocity component $v_z(z)$ change as functions of position z ($z=0$ at gate electrode). The value of t_{gt} is given by the sum of the time it takes to travel from the gate to the mesh electrode, t_{gm} , and from the mesh electrode to the target, t_{mt} ,

$$t_{gt} = t_{gm} + t_{mt} = \frac{v_z(L_{gm}) - v_z(0)}{a_{gm}} + \frac{v_z(L_{gm}) - v_z(L_{gt})}{a_{mt}}, \quad (A2)$$

where $a_{gm} = [(V_m - V_g)/L_{gm}] \times q/m$ is the electron acceleration between the gate and the mesh and $a_{mt} = [(V_m - V_t)/L_{mt}] \times q/m$ is the deceleration between the mesh and the target. Using energy conservation, i.e., $\frac{1}{2}m[v_z(z)^2 + v_x^2] = qV(z)$, we can obtain

$$v_z(z) = \sqrt{\frac{2qV(z)}{m} - \frac{2qV_g}{m} \sin^2 \theta}. \quad (A3)$$

By substituting $v_z(L_{gm})$ and $v_z(L_{gt})$ into Eq. (A2), t_{gt} can be obtained using

$$z = \begin{cases} v_x t + \frac{1}{2} a_{up} t^2 = t \sqrt{\frac{2eV_g}{m} \sin^2 \theta} + \frac{V_m - V_g}{2L_{gm}} \times \frac{e}{m} t^2 & (t < t_{gm}) \\ L_{gm} + v_x(t - t_{gm}) + \frac{1}{2} a_{down}(t - t_{gm})^2 = L_{gm} + (t - t_{gm}) \sqrt{\frac{2eV_g}{m} \sin^2 \theta} + \frac{V_m - V_t}{2L_{mt}} \times \frac{e}{m} (t - t_{gm})^2 & (t > t_{gm}) \end{cases}. \quad (A6)$$

Thus, the final lateral spread is given by $x(t=t_{gt})$ as

$$\begin{aligned} LS &= v_x \times t_{gt} \\ &= 2\sqrt{V_g} \sin \theta \cdot L_{gm} \left(\frac{\sqrt{V_m - V_g \sin^2 \theta} - \sqrt{V_g} \cos \theta}{V_m - V_g} \right) \\ &\quad + 2\sqrt{V_g} \sin \theta \cdot L_{mt} \left(\frac{\sqrt{V_m - V_g \sin^2 \theta} - \sqrt{V_t - V_g \sin^2 \theta}}{V_m - V_t} \right). \end{aligned} \quad (A7)$$

The lateral spread increases as θ increases while the other factors are kept constant. The condition for electrons to reach the target is $v_z \geq 0$ at $z = L_{gt}$. The critical θ_c occurs when $v_z = 0$. Thus, Eq. (A3) can be simplified to

$$\sin \theta_c = \sqrt{\frac{V_t}{V_g}}. \quad (A8)$$

The maximum lateral spread (LS_{max}) can be obtained by substituting Eq. (A8) into Eq. (A7),

$$\begin{aligned} LS_{max} &= 2\sqrt{V_t} \cdot L_{gm} \left(\frac{\sqrt{V_m - V_t} - \sqrt{V_g - V_t}}{V_m - V_g} \right) \\ &\quad + 2\sqrt{V_t} \cdot L_{mt} \left(\frac{1}{\sqrt{V_m - V_t}} \right). \end{aligned} \quad (A9)$$

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$$\begin{aligned} t_{gt} &= t_{gm} + t_{mt} = \frac{L_{gm}}{V_m - V_g} \sqrt{\frac{2m}{q} (\sqrt{V_m - V_g \sin^2 \theta} \\ &\quad - \sqrt{V_g} \cos \theta)} + \frac{L_{mt}}{V_m - V_t} \sqrt{\frac{2m}{q} (\sqrt{V_m - V_g \sin^2 \theta} \\ &\quad - \sqrt{V_t - V_g \sin^2 \theta})}. \end{aligned} \quad (A4)$$

Thus, the x and z location of an electron at any time t is given by

$$x = v_x \times t, \quad (A5)$$

and

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