Effect of repeated x-ray exposure on the resolution of amorphous selenium based x-ray imagers

M. Z. Kabir^{a)}

Department of Electrical and Computer Engineering, Concordia University, 1455 de Maisonneuve W., Montreal, Quebec H3G 1M8, Canada

L. Chowdhury and G. DeCrescenzo

Department of Medical Biophysics, Sunnybrook Health Sciences Centre, University of Toronto, 2075 Bayview Avenue, Toronto, Ontario M5S 2H3, Canada

O. Tousignant

ANRAD Corporation, 4950 Lévy Street, Saint-Laurent (Montreal), Quebec H4R 2P1, Canada

S. O. Kasap

Department of Electrical Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, Saskatchewan S7N 5A9, Canada

J. A. Rowlands

Department of Medical Biophysics, Sunnybrook Health Sciences Centre, University of Toronto, 2075 Bayview Avenue, Toronto, Ontario M5S 2H3, Canada and Thunder Bay Regional Research Institute, Lakehead University, 980 Oliver Road, Thunder Bay, Ontario P7B 6V4, Canada

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Purpose: A numerical model and the experimental methods to study the x-ray exposure dependent change in the modulation transfer function (MTF) of amorphous selenium (a-Se) based active matrix flat panel imagers (AMFPIs) are described. The physical mechanisms responsible for the x-ray exposure dependent change in MTF are also investigated.

Methods: A numerical model for describing the x-ray exposure dependent MTF of a-Se based AMFPIs has been developed. The x-ray sensitivity and MTF of an a-Se AMFPI have been measured as a function of exposure. The instantaneous electric field and free and trapped carrier distributions in the photoconductor layer are obtained by numerically solving the Poisson's equation, continuity equations, and trapping rate equations using the backward Euler finite difference method. From the trapped carrier distributions, a method for calculating the MTF due to incomplete charge collection is proposed.

Results: The model developed in this work and the experimental data show a reasonably good agreement. The model is able to simultaneously predict the dependence of the sensitivity and MTF on accumulated exposure at different applied fields and bias polarities, with the same charge transport parameters that are typical of the particular a-Se photoconductive layer that is used in these AMFPIs. Under negative bias, the MTF actually improves with the accumulated x-ray exposure while the sensitivity decreases. The MTF enhancement with exposure decreases with increasing applied field.

Conclusions: The most prevalent processes that control the MTF under negative bias are the recombination of drifting holes with previously trapped electrons (electrons remain in deep traps due to their long release times compared with the time scale of the experiments) and the deep trapping of drifting holes and electrons. © 2010 American Association of Physicists in Medicine. [DOI: [10.1118/1.3326947](https://doi.org/10.1118/1.3326947)]

Key words: ghosting, modulations transfer function, trapping, recombination, amorphous selenium, x-ray imagers

I. INTRODUCTION

Active matrix flat panel imagers (AMFPIs) based on a stabilized amorphous selenium (a-Se) photoconductor (direct conversion imagers) have been shown to provide excellent images, and have been recently commercialized by a number of companies for use in diagnostic medical digital x-ray imaging applications.^{1,2} Direct conversion imagers can experience a loss of sensitivity in subsequent exposures as a result of previous exposure to radiation, which is referred to as

ghosting. Bulk charge carrier trapping and the recombination between the trapped and oppositely charged drifting carriers is one of the major causes of ghosting.³ Recent experiments indicate that repeated exposure can also change the image resolution of a-Se imagers.⁴ Specifically, charge carrier trapping simultaneously reduces the sensitivity of direct conversion imagers and affects its resolution. The purpose of this paper is twofold. First, we develop a physical model and a technique to extract the modulation transfer function (MTF)

of an a-Se AMFPI as a function of the charge transport properties of the a-Se photoconductor, imager structure, operating conditions and, most importantly, as a function of accumulated exposure. The model is based on a model previously used to predict the reduction in sensitivity with exposure,³ and is explained in Sec. II. Second, we report new MTF measurements in which the change in sensitivity with exposure is measured simultaneously to ensure that history dependent effects in a-Se are adequately accounted for, as described in Sec. III. The model in Sec. II is then applied to the experimental MTF data to explain the observed improvements in the MTF with accumulated exposure under negative bias. The improvement in the MTF under negative bias was at first sight unexpected since the x-ray sensitivity has been shown to consistently deteriorate with accumulated exposure under both positive and negative bias voltages. However, it is shown in Sec. IV that the model is able to predict the experimental data and explain the general MTF behavior under negative bias condition with the same a-Se transport parameters; parameters that are typical of the a-Se photoconductor material. Further, the same model has been shown to explain the effect of ghosting in these imagers as well as to predict the MTF under positive bias. Thus, the most impressive feature of the model is its ability to explain both the measured MTF and sensitivity as a function of accumulated exposure at different applied fields using typical a-Se charge transport parameters.

The direct conversion AMFPI consists of a photoconductor layer sandwiched between two electrodes; the electrode at one surface is a continuous metal plate and the electrode on the other surface of the photoconductor is segmented into an array of individual square pixels of size $a' \times a'$ as shown in Fig. 1(a) held at ground potential. A bias voltage V is applied to the radiation-receiving electrode (top electrode) to establish an electric field in the photoconductor. As a result of image irradiation, a latent image charge accumulates on the pixel electrodes. There is a small gap between the pixel electrodes but due to electric field bending this has negligible effects.⁵ Some of the x-ray generated charge carriers get trapped in the bulk of the a-Se photoconductor layer during their drift toward the electrodes. Suppose that a carrier is trapped in the photoconductor above a particular reference pixel electrode of a pixelated image sensor. This trapped carrier induces charges not only on this pixel electrode but also on its neighboring pixels as shown in Fig. 1(b); consequently, there is a lateral spread of information and hence a loss of image resolution.

The characteristic detrapping (i.e., release) times for trapped charge carriers in a-Se are of the order of several minutes (holes) and hours (electrons).⁶ Therefore, on the time scale of repeated x-ray exposures in the clinic, trapped holes are released quickly, but trapped electrons accumulate in the bulk of the a-Se layer. The effects of bulk carrier trapping in a negatively biased AMFPI can be summarized as follows: (i) Electrons that become trapped during the course of an exposure cause a reduction in both the sensitivity and MTF. This appears to be the prevalent effect in our rested (previously unexposed) AMFPIs; (ii) holes that become

FIG. 1. (a) A cross section of a direct conversion pixelated x-ray imager. An electron and a hole are generated at x' and drift under the influence of the electric field F . (b) Trapped carriers in the photoconductor induce charges not only on the central pixel electrode but also on neighboring pixel electrodes, spread the information, and hence reduce spatial resolution.

trapped during the course of an exposure also cause a reduction in sensitivity but an increase in MTF; (iii) some of the trapped electrons act as charge capture centers for drifting holes, and both vanish after recombination. The latter phenomenon has the same effect as hole trapping, i.e., a decrease in sensitivity and an increase in MTF; (iv) the trapped electrons reduce the number of available empty trapping centers, and thus reduce electron trapping in subsequent exposure cycles; and (v) with increasing accumulated exposure, a quasi-equilibrium condition is reached when the rate of recombination of mobile holes with trapped electrons is the same as the trapping rate of mobile electrons. At this point, a quasi-steady state has been reached and no further changes in sensitivity and MTF should take place.

Que and Rowlands⁷ evaluated the dominant components of the intrinsic spatial resolution in a-Se by considering the following effects: Ranges of primary photoelectrons, reabsorption of K -fluorescent x-ray photons, reabsorption of Compton scattered photons, charge carrier diffusion, the geometric effect due to oblique incidence of x rays, and a space charge effect. Later, Zhao and Rowlands⁸ formulated an additional effect—The MTF due to carrier trapping at a fixed surface (parallel to the pixel plane) near the electrodes. More recently, Kasap and Rowlands⁹ discussed the dominant causes for the loss of resolution in photoconductive imagers including the loss of resolution due to bulk trapping. It has been found that, for diagnostic energy x rays, the most important mechanisms responsible for the loss of resolution in

a-Se imagers are charge carrier trapping, range of primary photoelectrons, reabsorption of *K*-fluorescent x-ray photons, pixel aperture, and geometric effects.

Kabir and Kasap (KK) have developed¹⁰ a static model for studying the resolution in terms of the MTF due to distributed bulk trapping of charge carriers, which is applicable for a single x-ray exposure. The model neglects the recombination of carriers and is based on deep trapping of carriers, as would be the case in the first exposure cycle under low-dose single shot experiments, and thus cannot be used to explain the changes in the MTF with accumulated exposure. (It was, however, successfully applied to CdZnTe based AM-FPIs to explain their MTF.¹⁰) Nonetheless, the KK model¹⁰ predicted that the trapping of the carriers that move toward the pixel electrodes degrades the MTF performance, whereas the trapping of the other type of carriers that move away from the pixels improves the high frequency components and thus enhances the sharpness of the x-ray image. In this paper, we further develop and enhance the KK model¹⁰ by including repeated exposure cycles and the recombination of drifting carriers with oppositely charged trapped carriers to extract the MTF (in Sec. II). This extended and enhanced theoretical model is compared to the measured data on sensitivity and MTF as a function of exposure. The comparison of the model with the experimental data reveals a quantitative explanation of the mechanisms that are responsible for the change in resolution with exposure while simultaneously explaining the loss of sensitivity.

II. THEORY

As a result of x-ray irradiation, electron-hole pairs (EHPs) are generated throughout the bulk of the photoconductor. The signal produced on a given pixel by a carrier is the difference between the instantaneous charge it induces on the pixel at the beginning and end of its journey across the photoconductor. Under negative bias, the holes then proceed toward the bias electrode and the electrons toward the active matrix. During its journey, a carrier may become trapped; it may recombine with a trapped carrier of opposite polarity, or proceed to its destination electrode uninterrupted. We denote the component of the MTF that depends on charge collection as MTF_{CC} . To understand the effect of charge trapping and recombination on MTF_{CC} , it is convenient to separately consider the MTFs of electrons and holes. MTF_{CC} is the sum of individual hole and electron MTFs.

Consider an EHP generated near the middle of the imager as depicted in Fig. 2(a). In their starting position, the electron and hole induce broad charge distributions of equal magnitude and opposite polarity on the active matrix pixel electrodes, and the net induced charge at any electrode is zero. As the hole drifts and finally reaches the bias electrode, the charge induced on the pixels reduces to zero. As for the electron, when it reaches a pixel, all of its charge is induced exclusively on that pixel. If both the electron and hole reach the electrodes (i.e., no trapping case), the induced charge distribution is represented mathematically by a delta function and the MTF_{CC} is unity at all frequencies as shown in Fig.

FIG. 2. (a) An illustration of an EHP that is generated in the bulk of the photoconductor. The hole moves toward the biased electrode at the top while the electron moves toward the pixels at the bottom. (b) The LSF is due to electron trapping (and no hole trapping). (c) The LSF is due to hole trapping (and no electron trapping). (d) The MTF_{CC} for no trapping of charge carriers. (e) The MTF_{CC} that decreases with spatial frequency caused by the trapping of electrons. (f) The trapping and recombination of holes generate an MTF_{CC} that increases with spatial frequency. For the purpose of this illustration, the usual unity normalization of the MTF_{CC} at zero frequency was omitted.

2(d). When the hole reaches the bias electrode and the electron is trapped in the a-Se layer, the resulting induced charge at the pixels is illustrated in Fig. 2(b). For this case, the MTF_{CC} will drop with spatial frequency as shown in Fig. 2(e). On the other hand, if the hole is trapped in the a-Se layer and the electron reaches a pixel, the trapped hole induces a broad negative charge distribution and the electron induces a delta function positive charge on that pixel. The resultant induced charge distribution at the pixels is illustrated in Fig. 2(c), which leads to a MTF_{CC} as illustrated in Fig. 2(f). Thus, the trapping of holes (i.e., charges which drift toward the bias electrode) generates a MTF_{CC} that increases with frequency.¹⁰ Hence, charge carriers of opposite signs have a complementary effect on the frequency dependence MTF_{CC} of the imager, and appear to cancel each other. However, the extent of the cancellation depends on the depth at which the x rays are absorbed and the lifetime of the carriers. The MTF reduction or enhancement due to trapping of both electrons and holes as a function of carrier lifetimes and absorption depth of x rays are described in detail in Ref. 10. It is important to note that when a free carrier recombines with a trapped charge of the opposite sign (that is, trapped in a previous exposure), its effect on the overall MTF of the imager is the same as that of a free carrier being trapped in the bulk. Note that the physical carrier movement is one-dimensional but this can induce signal in the transverse directions. To develop a model for calculating MTF_{CC} , we need to first determine the dose dependent free and trapped carrier distributions in the photoconductor layer.

II.A. Carrier dynamics

We consider an x-ray imager in which a photoconductor has been sandwiched between two large area parallel plate electrodes and biased with a voltage V applied to the

radiation-receiving electrode (top electrode) to establish an electric field in the photoconductor. The charge is collected at the bottom electrode.

We assume that the thermal equilibrium carrier concentrations are negligibly small and that the dark current is negligible compared to the x-ray photocurrent. The diffusion of carriers is negligible compared to their drift because of the high field applied across the photoconductor. The general transport behavior in a-Se can be described in terms of only one effective set of deep traps for each carrier that controls its lifetime τ' .^{11–13} Therefore, it is reasonable to assign a constant drift mobility μ and a single deep trapping time (lifetime) τ' to each type of carrier (holes and electrons). Note that the effect of shallow traps on charge transport is incorporated in the drift mobility, which is less than the actual drift mobility in the transport band. Defining $p'(x', t')$ as the free hole concentration, $n'(x', t')$ as the free electron concentration, $p'_t(x', t')$ as the trapped hole concentration, and $n'_t(x', t')$ as the trapped electron concentration at point x' at time t' , the continuity equations under negative bias for electrons and holes are

$$\frac{\partial n'}{\partial t'} = -\mu_e \frac{\partial(n'F')}{\partial x'} - \frac{n'}{\tau'_e} - C_e n' p'_t + g(x', t') e^{-\alpha x'}, \quad (1)$$

$$\frac{\partial p'}{\partial t'} = \mu_h \frac{\partial(p'F')}{\partial x'} - \frac{p'}{\tau'_h} - C_h p' n'_t + g(x', t') e^{-\alpha x'}, \quad (2)$$

where x' is the distance from the radiation-receiving electrode (Fig. 1), $F'(x', t')$ is the electric field in the photoconductor at point x' and time t' , $g(x', t')$ is the EHP generation rate, α is the x-ray linear attenuation coefficient of the photoconductor, C_e is the capture coefficient between free electrons and trapped holes, and C_h is the capture coefficient between free holes and trapped electrons. The subscripts e and h represent electrons and holes, respectively. For an a-Se photoconductor, a recombination-type capture process follows the *Langevin recombination* mechanism^{14,15} and thus $C_h = e\mu_h/\varepsilon$ and $C_e = e\mu_e/\varepsilon$, where e is the elementary charge and ε ($=\varepsilon_0\varepsilon_r$) is the permittivity of the photoconductor.

If we also consider the trap filling effect and x-ray induced new deep trap center generation, the trapping times for electrons and holes become, respectively,

$$\tau'_e = \frac{\tau'_{0e}}{1 + (N_{Xe} - n_t)/N_{0e}}, \quad (3)$$

$$\text{and } \tau'_h = \frac{\tau'_{0h}}{1 + (N_{Xh} - p_t)/N_{0h}}, \quad (4)$$

where N_X is the concentration of x-ray induced deep trap centers, N_0 is the concentration of initial deep trap centers, and τ'_0 is the initial carrier trapping time. The concentration of exposure induced deep trap centers depends on the photoconductor material, imager operating conditions, the irradiation energy, and the amount of exposure. The exposure induced deep trap center generation kinetics is taken to be a first order rate equation so that^{16,17}

$$N_{Xe} = N_{se}(1 - e^{-X/D}), \quad (5)$$

$$N_{Xh} = N_{sh}(1 - e^{-X/D}), \quad (6)$$

where N_s is the saturation value of the x-ray induced deep trap centers, D is an irradiation energy dependent constant, and X is the amount of accumulative (or total) exposure. Obviously, under low exposure conditions, N_{Xe} and N_{Xh} increase linearly with X .

It is well known that the a-Se structure has valence alternation pair type defects and must also have seemingly “neutral” trap centers such as intimate valence alternations pairs. These trap centers can also interconvert.¹⁸ Therefore, only a certain fraction f_r of trapped charges act as recombination centers for drifting carriers.^{3,16} Using a simple correction factor f_r avoids introducing another set of deep traps into Eqs. (1) and (2) with different capture cross sections and different release times, and another set of rate equations in addition to Eqs. (9) and (10) below. For simplicity, we use the normalized distance coordinates x , y , and z , where $x=x'/L$, $y=y'/L$, $z=z'/L$, and L is the photoconductor layer thickness, to yield the normalized attenuation depth $\Delta=1/\alpha L$, the normalized pixel aperture width $a=a'/L$, and normalized spatial frequency $f=f'L$, in which f' is the actual spatial frequency (the conventional unit is mm^{-1}). The time coordinate is normalized with respect to the transit time of electrons t_e ($t_e=L/\mu_e F_0$, where $F_0=V/L$, t_e is the longest transit time), which are the slowest carriers. Therefore, the normalized time coordinate $t=t'/t_e$ and normalized carrier lifetimes $\tau_e=\mu_e\tau'_e F_0/L$ and $\tau_h=\mu_h\tau'_h F_0/L$. The normalized electric field $F=F'/F_0$. Charge carrier concentrations are normalized with respect to the total photogenerated charge carriers per unit area, Q_0 (electrons/ m^2) in the photoconductor as if the total charge carriers is uniformly distributed over the sample volume. The expression for Q_0 is available in Ref. 3.

The continuity Eqs. (1) and (2) can now be recast into the dimensionless forms

$$\frac{\partial n}{\partial t} = -\frac{\partial(nF)}{\partial x} - \frac{n}{\tau_e} - f_r c_0 n p_t + K e^{-x/\Delta}, \quad (7)$$

$$\frac{\partial p}{\partial t} = r_\mu \frac{\partial(pF)}{\partial x} - r_\mu \frac{p}{\tau_h} - f_r c_0 r_\mu p n_t + K e^{-x/\Delta}, \quad (8)$$

where $r_\mu=\mu_h/\mu_e$, $c_0=eQ_0/\varepsilon F_0$, $n=n'/p_0$, $p=p'/p_0$, $n_t=n'_t/p_0$, $p_t=p'_t/p_0$, $p_0=Q_0/L$, $K(x,t)=\{t_e W_0\}/\{T_x \eta \Delta W(x,t)\}$, $\eta=1-\exp(-1/\Delta)$, and T_x is the exposure time. The ratio $W_0/W(x,t)=g(x,t)/g_0$. $W(x,t)$ is the EHP creation energy at the instantaneous electric field $F(x,t)$, and W_0 (W_0 is in eV) and g_0 are the EHP creation energy and EHP generation rate in the photoconductor at F_0 . The trapping rate equations in normalized forms are

$$\frac{\partial n_t}{\partial t} = \frac{n}{\tau_e} - f_r c_0 r_\mu p n_t, \quad (9)$$

$$\text{and } \frac{\partial p_t}{\partial t} = r_\mu \frac{p}{\tau_h} - f_r c_0 n p_t. \quad (10)$$

The Poisson's equation becomes

$$\frac{\partial F}{\partial x} = c_0[p + p_t - n - n_t]. \quad (11)$$

The nondimensionalized coupled partial differential Eqs. (7)–(11) are simultaneously solved by the finite difference method. The necessary initial conditions before any exposure are³

$$\begin{aligned} p(x,0) = 0, \quad n(x,0) = 0, \quad p_t(x,0) = 0, \\ n_t(x,0) = 0, \quad \text{and} \quad F(x,0) = 1. \end{aligned} \quad (12)$$

The boundary condition for electric field is given by

$$\int_0^1 F(x,t) dx = 1. \quad (13)$$

After EHP generation due to x-ray exposure, holes move toward the top electrode and electrons move toward the bottom electrode under negative bias. Immediately after the onset of x-ray exposure, the free electron concentration at $x=0$ and the free hole concentration at $x=1$ are zero since the carriers have started drifting.

The total normalized current density is given by¹⁹

$$j(t) = \int_0^1 F(x,t)[n(x,t) + r_{\mu}p(x,t)] dx. \quad (14)$$

The integration of current over the time period of interest is the normalized collected charge or charge collection efficiency. The product of the normalized collected charge and the quantum efficiency η represents the normalized x-ray sensitivity.

The trapped carrier concentrations at the end of one exposure cycle are carried forward as initial conditions in the next exposure cycle so that the effect of accumulated exposure can be properly modeled. The model also takes into account any detrapping of deeply trapped carrier in the time interval between two consecutive exposure cycles. Further, except for the first exposure cycle, the field inside the photoconductor prior to exposure would be determined by the net space charge density arising from the difference between the trapped hole and electron concentrations, that is, Eq. (11) with $p=n=0$. During exposure, however, the field would be determined by the net space charge density due to all carriers, both trapped and free carriers, as in Eq. (11).

II.B. MTF components

The signal transfer and scattering through a-Se detectors is a complex process. The analysis of signal formation and scattering can be systematized by the introduction of a cascaded linear system model.^{20,21} Three independent blurring stages are identified in the cascaded system model.^{20,21} These are (i) scattering of x-ray photons (this stage includes the range of primary photoelectrons, Compton scattering, and reabsorption of K -fluorescence x rays) before EHP generation, (ii) blurring due to incomplete charge collection, and (iii) aperture blurring. Therefore, the overall MTF is simply

the product of the MTFs of these three independent stages. Note that the MTFs of stages (i) and (iii) are independent of dose and the combined MTF of these two stages can be considered as the dose independent MTF, i.e., MTF_0 . Since the charge collection is considered as an independent stage in the cascaded system model, the total MTF, i.e., MTF_T can be expressed as⁴

$$MTF_T(f) = MTF_0(f) \times MTF_{CC}(f), \quad (15)$$

where $MTF_0(f)$ includes all dose independent causes such as Compton scattering, K -fluorescence, range of primary photoelectrons, pixel aperture, and geometric effects.

A series of high dose x-ray exposures (ghosting doses) is applied to the imager and the MTF after each ghosting dose is calculated. To calculate MTF after every ghosting dose, a very short pulse exposure (probe pulse) of radiation is considered. Since $MTF_0(f)$ is independent of dose and unchanged for all measurements, the relative MTF, i.e., MTF_r , after the n th ghosting dose can be written as

$$(MTF_r)_n = \frac{(MTF_T)_n}{(MTF_T)_0} = \frac{(MTF_{CC})_n}{(MTF_{CC})_0}, \quad (16)$$

where $(MTF_T)_0$ and $(MTF_{CC})_0$ are the initial (before any ghosting dose) MTF_T and MTF_{CC} , respectively. Note that all the MTF terms in Eq. (16) are frequency dependent. The relative MTF_r can be obtained from the measurement of MTF_T or from the calculation of dose dependent MTF_{CC} as described in Eq. (16).

II.C. Theoretical model for MTF_{CC}

The instantaneous electric field and free and trapped carrier distributions are obtained by numerically solving Eqs. (7)–(11). The trapped carrier distributions after every ghosting and probe pulse are hence calculated by considering recombination and trap filling under a nonuniform electric field and existing trapped charges. The effect of the recombination of a drifting carrier with an oppositely charged trapped carrier on MTF_{CC} is the same as that of a drifting carrier becoming trapped in the bulk.⁴ The difference between the calculated trapped carrier distribution after a probe pulse and that arising from the previous ghosting pulse is the actual trapped carrier distribution for that probe pulse and is used to calculate the MTF_{CC} .

The *geometric* pixel aperture width in a flat panel imager is smaller than the pixel pitch (center-to-center spacing between two pixels). However, it has been shown that the *effective* fill factor (the effective fraction of pixel area used for image charge collection) of a photoconductive flat panel imager is close to unity.^{1,5} Therefore, the effective pixel aperture width is virtually identical to the pixel pitch and the imager geometry is just like a parallel plate configuration from the electrostatic point of view, except that the currents through individual pixels are integrated separately. The induced charge density at the pixel plane (yz plane at $x=1$) due to a point charge at (x,y,z) in the photoconductor can be conveniently calculated by constructing an infinite series of image charges.²² The line spread function (LSF) along the y

FIG. 3. A schematic diagram for calculating LSF. The induced charge density at point P due to distributed bulk trapping in the xz plane (at $y=0$) is calculated, where P is an arbitrary point along the y axis.

axis at the pixel plane is calculated by considering induced charges along the y axis due to distributed bulk trapped charges in the xz plane at $y=0$, as shown in Fig. 3. The LSF can be written as¹⁰

$$L(y) = \frac{1}{2\pi} \int_0^1 \int_{-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \frac{q_t(x)(1-x+2k)}{[(1-x+2k)^2 + y^2 + z^2]^{3/2}} dz dx + Q_b \delta(y), \quad (17)$$

where m is an integer, $q_t(x) = n_t(x) - p_t(x)$ is the resultant normalized net trapped charge concentration for the probe x-ray beam under negative bias, and Q_b is the fraction of the generated carriers for the probe pulse that reach the pixel electrode (electrons reach the pixel electrode under negative bias).¹⁰ The subscripts t and b represent carriers that drift towards the top and bottom electrodes, respectively. Under positive bias, $q_t(x) = p_t(x) - n_t(x)$ and Q_b represent holes. The two terms in Eq. (17) are usually on the same order of magnitude while the second term for any practical detector is greater than the first term. The magnitude of the first term in Eq. (17) is the maximum at $y=0$, decreases with increasing $|y|$, and its shape is shown in Figs. 2(b) and 2(c). The polarity of the broad charge distributions due to the first term in Eq. (17) depends on the polarity of q_t . The expression for Q_b for the initial probe pulse is given by¹⁰

$$Q_b = \frac{\tau_b(e^{-1/\Delta} - e^{-1/\tau_b})}{\eta\Delta(1 - \tau_b/\Delta)}, \quad (18)$$

where $\eta = 1 - \exp(-1/\Delta)$ is the quantum efficiency of the imager. For negative bias, $\tau_b = \tau_e$. The one-dimensional Fourier transform of $L(y)$ is (see Appendix)

$$G(f) = \int_0^1 q_t(x) \frac{\sinh(2\pi fx)}{\sinh(2\pi f)} dx + Q_b. \quad (19)$$

The MTF due to carrier trapping is isotropic on the pixel plane (yz plane). Therefore, the frequency f refers to the spatial frequency that corresponds to any direction on the pixel plane. The magnitude of the first term in Eq. (19) is the

maximum at $f=0$ and it decreases with increasing f . If there is hole trapping and no electron trapping (n_t is zero, q_t is negative, and Q_b is positive), the first term in Eq. (19) is negative and thus $G(f)$ increases with increasing f . In this case, the MTF_{CC} improves with spatial frequency, which is consistent with Fig. 2(f). On the other hand, when there is electron trapping and no hole trapping (p_t is zero, q_t is positive, and Q_b is positive), the first term in Eq. (19) is positive, and thus $G(f)$ decreases with increasing f . In this case, the MTF_{CC} will drop with spatial frequency, which is consistent with Fig. 2(e). If all the carriers are trapped at a distance x (parallel to the pixel plane), then $Q_b=0$, $q_t(x)=\delta(x)$, and $G(f)=\sinh(2\pi fx)/\sinh(2\pi f)$, which is exactly the same equation for MTF due to carrier trapping at a fixed surface obtained by Zhao and Rowlands.⁸

For the distributed carrier trapping, the expression for $G(f=0)$ is

$$G(0) = \int_0^1 x q_t(x) dx + Q_b. \quad (20)$$

The MTF due to the trapped carriers belonging to the probe pulse is given by (in order to get the usual unity normalization of the MTF_{CC} at zero frequency)

$$\text{MTF}_{\text{CC}}(f) = \frac{G(f)}{G(f=0)}. \quad (21)$$

Note that the $q_t(x)$ for the probe beam is calculated by solving the one-dimensional transport equations. In other words, the carrier spreading due to the Coulomb force between them and the lateral carrier diffusion phenomena are neglected in the formulation of the MTF_{CC} . Each x-ray photon absorbed in a-Se creates a cloud of charge carriers. A lateral motion of charge carriers is expected due to the Coulombic repulsive force between them during their travel toward the electrodes. Que and Rowlands⁷ had estimated the maximum lateral displacement of charge carriers due to the Coulombic force between them, which is less than $0.1 \mu\text{m}$ for 50 keV, incident x rays, $L=1 \text{ mm}$, and $F=10 \text{ V}/\mu\text{m}$ (the usual applied field in a-Se imagers). Therefore, this effect is obviously negligible. Que and Rowlands⁷ had also estimated the MTF due to carrier diffusion through the whole a-Se layer by the expression, $\text{MTF}_d(f) \sim \exp(-\pi^2 f'^2 \sigma^2)$, where $\sigma^2 = 4kTL/(eF)$, k is the Boltzmann constant, and T is the absolute temperature. For $T=300 \text{ K}$, $L=1 \text{ mm}$, $a'=150 \mu\text{m}$, and $F=10 \text{ V}/\mu\text{m}$, we obtain $\sigma=0.01 \text{ mm}$ ($10 \mu\text{m}$) and $\text{MTF}_d(f=f_N) \approx 0.99$ at the Nyquist frequency $f_N=3.33 \text{ lp/mm}$. The average MTF_d , considering the exponential x-ray absorption profile, should be even higher than the above estimated value. Therefore, the effect of lateral diffusion on MTF in a-Se imagers can be neglected.

III. EXPERIMENTAL PROCEDURE

III.A. Flat panel imager

The imager used for our measurements was an a-Se direct conversion AMFPI developed and manufactured by ANRAD Corporation (Quebec, Canada). It consisted of a 1 mm thick

layer of stabilized a-Se (a-Se alloyed with 0.2%–0.5% As and doped with 10–40 ppm Cl) photoconductor evaporated onto a 14×14 in² active matrix array and associated electronics. The active matrix was an array of 2304×2304 pixels with a pitch of $150 \mu\text{m}$ in both directions. During x-ray exposure, the gate line voltages are such that the thin film transistors (TFTs) are turned off and a latent image stays in the storage capacitors. Following the exposure, all gate lines are driven to turn on the TFT switches in a sequential manner, one row at the time, which allows the charge transfer to the charge amplifier channel. To carry out the MTF measurements, we constructed an edge-mounting frame made from two sheets of Plexiglas between which a tungsten plate with a straight edge could be slid and securely positioned in a highly repeatable manner. The latter construction was mounted on the front surface of the AMFPI. The AMFPI was setup at full resolution readout mode resulting in an image of 2304×2304 pixels.

Prior to the experiments, the panel had been rested, i.e., it was not subjected to any radiation and no electric field was applied to its a-Se layer for at least 24 h before the start of the experiment. At the beginning of the experiment, a negative bias voltage of 10 kV was applied to the bias electrode of the panel to establish an electric field of $F_0 = 10 \text{ V}/\mu\text{m}$ across the a-Se layer. The gain and offset calibrations were performed at 120 kVp at least 24 h prior to the measurement to allow the panel to return to a rested state. All the measurements in this paper are performed on the same imager.

III.B. MTF and sensitivity measurement

A tungsten plate measuring $16.6 \times 5.3 \times 0.3 \text{ cm}^3$ was used to measure the MTF using the slanted edge technique.^{23,24} The edge (ground side) of the W plate was positioned on the mounting frame described above at $\sim 2^\circ$ with respect to the vertical edge of the panel. A sequence of 13 images of the edge were taken using a low intensity (5.4 mR), the MTF probing beam of 120 kVp hardened by a 21 mm aluminum filter (effective photon energy is 58 keV). The choice of a highly penetrating beam allowed us to probe the entire 1 mm thickness of the a-Se layer. Each probing image was obtained using a low exposure (a few mR) to avoid disturbing the state of the panel. These images were averaged to reduce noise and the resulting image was used for the calculation of the initial MTF, $(\text{MTF}_T)_0$. A small portion of the averaged images, located far from the edge, was used to measure the change in sensitivity. The edge was subsequently removed from the mounting frame and the entire panel was uniformly irradiated with a ghosting beam of 50 kVp. A 50 kVp x-ray beam of 1 R exposure used to create the ghosting dose with an effective photon energy of 36 keV. The purpose of this exposure was to permit the trapping of electrons and holes. The choice of a low kVp has the effect of enhancing the trapping of electrons. At low kVp, charge carriers are generated primarily in the vicinity of the negative electrode. As a result, the electrons have to travel, on average, a greater distance than the holes, leading to the desired increase in trapping. The edge was repositioned on the panel

FIG. 4. Relative sensitivity change as a function of accumulated dose for applied fields of 10 and $5 \text{ V}/\mu\text{m}$. The symbols are experimental data and the solid lines are theoretical fits to the experimental data.

and a new set of probe images were acquired. These images were averaged to obtain $(\text{MTF}_T)_n = 1$. This entire procedure was repeated $n-1$ more times and $(\text{MTF}_T)_n$ obtained with a corresponding measurement of sensitivity. The experiment was then repeated with $F_0 = 5 \text{ V}/\mu\text{m}$.

To obtain the $(\text{MTF}_T)_n$ values from the averaged edge images, we calculated the integer number of rows n_R leading to a shift of 1 pixel of the edge with respect to the array of pixels. For a 2° slant, $n_R = 29$. Each group of n_R lines gives a single oversampled edge spread function (ESF). Using the central (7.5 cm) portion of the edge image, several oversampled ESFs were extracted (typically 16) which, after appropriate shifting to correct for the slant, were averaged together to obtain the final oversampled ESF. The ESF was differentiated to find the LSF and the modulus of the Fourier transform of the LSF was taken as the $(\text{MTF}_T)_n$ of the panel.

IV. RESULTS AND DISCUSSION

Figure 4 shows the theoretical and measured relative x-ray sensitivity as a function of exposure at two different applied fields: $F_0 = 10 \text{ V}/\mu\text{m}$ and $F_0 = 5 \text{ V}/\mu\text{m}$. The normalization is done by dividing the x-ray sensitivity with the initial sensitivity, that is, the sensitivity of a well rested AMFPI before any x-ray exposure. The applied bias on the radiation-receiving electrode is negative, and the thickness of the photoconductor layer L is 1.0 mm. The theoretical normalized x-ray sensitivity for the 120 kVp probe beam is calculated using an effective photon energy of 58 keV. The drift mobility-lifetime products of carriers (i.e., carrier ranges) are assumed to be $\mu_h \tau'_{oh} \approx 3.5 \times 10^{-5} \text{ cm}^2/\text{V}$ and $\mu_e \tau'_{oe} \approx 4.0 \times 10^{-6} \text{ cm}^2/\text{V}$, which are very reasonable values for the photoconductive material used.¹¹ The hole detrapping time is assumed as $\tau_{dh} \approx 15 \text{ min}$ (using the location of deep traps in the mobility gap)²⁵ and $N_0 \approx 2 \times 10^{12} \text{ cm}^{-3}$ for both holes and electrons, using a deep trapping capture coefficient $C_t \approx 10^{-8} \text{ cm}^3 \text{ s}^{-1}$.²⁶ It is apparent that there is a good agreement between the proposed model and the experimental data. The fitted values of N_{se} , N_{sh} , and D are $2.5 \times 10^{12} \text{ cm}^{-3}$,

FIG. 5. The measured MTFs after a uniform ghosting dose of 0, 2, 4, and 8 R at the applied field of (a) 10 and (b) 5 V/ μm .

$1.5 \times 10^{12} \text{ cm}^{-3}$, and 2 R, respectively. The fitted values of f_r are 0.5 and 0.25 for $F_0 = 10 \text{ V}/\mu\text{m}$ and $F_0 = 5 \text{ V}/\mu\text{m}$, respectively. This is in agreement with previous results that f_r increases slightly with increasing applied electric field.^{3,16} The sensitivity decreases with accumulated dose, which is also consistent with our previous reports.³ Figures 5(a) and 5(b) show the measured MTFs for a negatively biased a-Se imager after exposure to a 50 kVp uniform ghosting dose of 0, 2, 4, and 8 R at the applied fields of 10 and 5 V/ μm , respectively. The MTF actually improves with the ghosting dose because of the improvement in MTF_{CC} as discussed below.

Figure 6 shows the MTF_r as a function of accumulated exposure for a negatively biased a-Se imager operating at F_0 of 10 V/ μm . The dotted and dashed lines represent experimental data and the solid lines represent theoretical fits to the experimental data. Equation (16) is used to calculate and measure the MTF_r . The photoconductor layer thickness $L = 1.0 \text{ mm}$. All the transport and fitting parameters for MTF in Fig. 6 are the same as those for the sensitivity in Fig. 4. There is a reasonably good agreement between the proposed model and the experimental data given that the same fitting

FIG. 6. MTF_r as a function of x-ray exposure for a negatively biased a-Se imager. The dotted and dashed lines represent experimental data and the solid lines represent theoretical fits to the experimental data.

parameters were used for the sensitivity and the MTF. For the 120 kVp x-ray beam, the carrier generation is almost uniform across the photoconductor thickness, and both holes and electrons play almost equal roles in the charge collection process. The MTF improves with ghosting doses, accumulated x-ray exposure, as evident from Fig. 6. It has been found previously¹⁰ that the trapping of the carriers that move toward the pixel electrodes (electrons in this case) degrades the high frequency components of the MTF, whereas trapping of the oppositely charged carriers that move away from the pixels (holes in this case) improves the high frequency components of the MTF curve. The high frequency components of the MTF increases with accumulated exposure (Fig. 6), which indicates the relative trapping of electrons decreases and/or the trapping (including the recombination) of holes increases with increasing exposure. The recombination of holes with trapped electrons increases with increasing exposure but the trapping of electrons decreases due to the trap filling effect. The rate of change in the MTF_r decreases with increasing accumulated exposure, and eventually, the MTF approaches a saturation value. After this point, the carrier dynamics reaches an approximate state of equilibrium, as described in Sec. I. This is not a total equilibrium, however, but a substantial decrease in the rate of change in sensitivity and MTF with the ghosting exposure. The latter effect may be explained by the continuing creation of new radiation-induced trap centers.¹⁷ (The new trap centers are likely to be metastable and slowly anneal out due to structural relaxation effects.)

Figure 7 shows the MTF_r after a total exposure of 12 R for a negatively biased a-Se imager and for different applied fields ($F_0 = 5$ and 10 V/ μm). The dotted lines represent experimental data and the solid lines represent theoretical fits to the experimental data. There is a reasonably good agreement between the proposed model and the experimental data. The MTF_r enhancement with exposure increases with decreasing applied field. The effects of trapping and recombination increase with decreasing electric field, which leads to an improved MTF as the field is reduced. It should be emphasized

FIG. 7. MTF_r as a function of various applied fields after a total x-ray exposure of 12 R for the negatively biased a-Se detector. The dotted lines represent experimental data and the solid lines represent theoretical fits to the experimental data.

that all the transport and fitting parameters used in the calculations for generating the theoretical curves in Fig. 7 are the same as those in Figs. 4 and 6. In other words, the same transport and fitting parameters are able to explain all the observed MTF and sensitivity vs ghosting exposure data at different fields and under different amounts of accumulate exposure.

Figure 8 shows the theoretical MTF_r after a total exposure of 12 R for two probe x-ray beams of 50 and 120 kVp. The MTF_r is less affected by the 50 kVp probe x-ray beam than it is by the 120 kVp probe x-ray beam. The reason is that at 50 kVp, the electrons and holes are mainly generated near the radiation-receiving electrode. The holes, therefore, must travel, on average, a smaller distance than they do in the case of 120 kVp beam exposure. Consequently, there is less trapping of holes under 50 kVp exposure, and hence less MTF variation with ghosting exposure.

Figure 9 shows the MTF_r after an accumulated ghosting dose of 12 R under positive bias for two applied fields of $F_0 = 10$ V/ μ m and $F_0 = 5$ V/ μ m. The MTF_r deteriorates un-

FIG. 8. Theoretical MTF_r for two probe x-ray beams of different energies after a total exposure of 12 R for a negatively biased a-Se imager.

FIG. 9. Theoretical MTF_r for two applied fields of $F_0 = 10$ V/ μ m and $F_0 = 5$ V/ μ m after a total exposure of 12 R for a positively biased a-Se imager showing a reduction, as opposed to the increase seen for the negatively biased imagers.

der positive bias and the deterioration increases with decreasing applied electric field. The relative amount of trapping and recombination of holes increases because of the recombination of the drifting holes with trapped electrons. In addition, the trap filling effect decreases the capture of electrons. Since, under positive bias, holes move toward the pixelated bottom electrode, the MTF_r deteriorates with exposure. However, it is evident by comparing Figs. 6 and 9 that the change in the MTF under positive bias is not as significant as that under negative bias.

V. SUMMARY AND CONCLUSIONS

A physical model with numerical solutions for describing the x-ray exposure dependent MTF in flat panel a-Se x-ray imagers has been proposed. The model includes the following factors: (a) Trapping of carriers into deep traps; (b) recombination of drifting carriers with oppositely charged carriers in deep traps; (c) trap filling effects; (d) release from traps (in particular for holes); (d) the modification of the internal field due to deep trapping (build-up of net space charge); (e) modification in charge transport and trapping due to a nonuniform internal field; (f) modification of the photogeneration efficiency due to a nonuniform field; and (g) x-ray induced creation of additional traps. We use MTF measurements and sensitivity measurements made simultaneously to ensure that history dependent effects in a-Se are identical for both. We are able to explain the measured MTF plotted as a function of accumulated exposure data, under different applied fields and bias polarity by using the same charge transport parameters and imager properties. Further, the transport parameters for the model are typical values found for the a-Se photoconductor used in the imager, which provides strong independent support for the model. We have shown that the MTF under negative bias improves with accumulated x-ray exposure. This MTF enhancement with exposure increases with decreasing applied field. The improvement in the high frequency components of the MTF curve is

more pronounced for higher x-ray energies. The change in MTF with accumulated x-ray exposure under negative bias is much more significant than that under positive bias. Keeping all the transport and fitting parameters the same, the proposed model fits both the experimental data on changes in the sensitivity and MTF; this is the strongest feature of the model presented. The most significant reason for the observed enhancement in the MTF is the recombination of drifting holes with trapped electrons from a previous exposure cycle. As the imager is repeatedly exposed, a quasi-steady state is eventually reached when the rate of change in the sensitivity and the MTF becomes small, and limited by the rate of change in the x-ray induced creation of traps. In the quasisteady state, the deep electron traps become heavily populated (the so-called trap filling effect), which reduces further electron trapping. The reduction in the electron trapping means a reduction in the rate of recombination between drifting holes and trapped electrons in the next exposure cycle. Thus, while the change in MTF of a-Se AMFPI is at first surprising, it can be fully understood in terms of the

known trapping properties of a-Se without further assumptions when the previously known parameters are inserted into the present model for MTF. From a practical point of view, the changes in sensitivity and MTF can be modeled to sufficient accuracy to permit their correction, if desired.

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APPENDIX: FOURIER TRANSFORM

The Fourier transform of Eq. (17) is given by

$$G(f) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_0^1 \int_{-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \frac{q_t(x)(1-x+2k)}{[(1-x+2k)^2 + y^2 + z^2]^{3/2}} \times e^{-j2\pi fy} dz dx dy + \bar{Q}_b. \quad (\text{A1})$$

Changing the order of integrations, Eq. (A1) becomes

$$\begin{aligned} G(f) &= \frac{1}{2\pi} \int_0^1 q_t(x) \sum_{k=-\infty}^{\infty} (1-x+2k) \int_{-\infty}^{\infty} e^{-j2\pi fy} \int_{-\infty}^{\infty} \frac{1}{[(1-x+2k)^2 + y^2 + z^2]^{3/2}} dz dy dx + \bar{Q}_b \\ &= \frac{1}{\pi} \int_0^1 q_t(x) \left\{ \sum_{k=0}^{\infty} (1-x+2k) \int_{-\infty}^{\infty} \frac{e^{-j2\pi fy}}{[(1-x+2k)^2 + y^2]} dy - \sum_{k=1}^{\infty} (2k-1+x) \int_{-\infty}^{\infty} \frac{e^{-j2\pi fy}}{[(2k-1+x)^2 + y^2]} dy \right\} dx + \bar{Q}_b \\ &= \int_0^1 q_t(x) \left\{ \sum_{k=0}^{\infty} e^{-2\pi f(1-x+2k)} - \sum_{k=1}^{\infty} e^{-2\pi f(2k-1+x)} \right\} dx + \bar{Q}_b \\ &= \int_0^1 q_t(x) \left\{ \frac{e^{-2\pi f(1-x)}}{1-e^{-4\pi f}} - \frac{e^{-2\pi f(x-1)}}{1-e^{-4\pi f}} + e^{-2\pi f(x-1)} \right\} dx + \bar{Q}_b \\ &= \int_0^1 q_t(x) \frac{\sinh(2\pi fx)}{\sinh(2\pi f)} dx + \bar{Q}_b. \end{aligned} \quad (\text{A2})$$

^{a)} Author to whom correspondence should be addressed. Electronic addresses: kabir@encs.concordia.ca; Fax: +1 514 8482802.

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