Dependence of Modulation Transfer Function on Electric Field Intensity of Photo conductor and Mobility-lifetime Product of Carriers in Polycrystalline Mercuric Iodide Based Flat Panel X-Ray Detectors: A Quantitative Approach and Error Analysis

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Abstract

Objective: In this Paper, a simplified mathematical model for Modulation Transfer Function (MTF) of Polycrystalline Mercuric Iodide based flat panel x-ray detector is applied on three different published prototypes of Polycrystalline Mercuric Iodide. Our aim was to fit the curves generated by simulation of MTF model with the curves acquired from experimental data. Method: Varied Electric field was employed to obtain the best fitting. Findings: The mobility-lifetime product for the best curve fitting was examined for each prototype. Percentage of fitting error has been estimated for each prototype. Finally, average absolute error has been calculated for all the incorporated prototypes. Application: This study can be further extended to develop a generic empirical model for the Modulation Transfer Function of polycrystalline mercuric iodide based flat panel x-ray detectors.

Keywords: Average Absolute Error, Electric Field Intensity, Empirical Model, Error Analysis, Mobility-Lifetime Product, Modulation Transfer Function

1. Introduction

Flat panel direct conversion digital x-ray image detectors consisting of a photoconductor and an active matrix array of segmented square pixels have been replacing traditional film-based diagnostic medical x-ray imaging systems for the past few years. With its application increasing, there has been an active research to find potential alternative x-ray photoconductors to replace the traditionally used a-Se based photoconductors especially in low-exposure flat panel image detectors primarily because of the drawback of a-Se detector that it has a low conversion gain limiting the x-ray imaging performance at low exposure. Polycrystalline Mercuric Iodide (poly-HgI2) based photoconductor is such a potential alternative with substantially lower Electron-Hole Pair (EHP) creation energy and operating electric field compared to a-Se based photoconductor.

Modulation Transfer Function (MTF) measures the efficiency of an imaging system such as a detector to resolve (transfer) different spatial frequencies of information in an image. In the measurement process of MTF, mobility-lifetime product of electrons and holes is a very important parameter as sensitivity of photoconductor greatly depends on the value of it.

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In paper\textsuperscript{3}, used a simplified mathematical model\textsuperscript{1} for MTF on various Published\textsuperscript{4} prototypes of Mercuric Iodide. However, in paper\textsuperscript{2} the authors kept the photoconductor electric field constant for their simulations. In this study, the effect of the variation of photoconductor electric field is examined. Our simulation results show a good agreement with experimental data for every prototype for a certain value of electric field and mobility-lifetime product. Percentage of error in the fitting has been estimated for each prototype. Finally, average absolute fitting error has been obtained for each prototype to assess the closeness of the fitting.

2. Model and Simulation

Resolution or modulation transfer function is determined from Line Spread-Function. The Line Spread-Function (LSF) is defined as the sum of the spatial distribution of illuminance in the front and the back emulsion caused by a beam of x rays which passes through photoconductor slit\textsuperscript{5}. Fourier transformation of the LSF gives the corresponding Modulation Transfer Function (MTF). For mathematical model, we have used the Line Spread Function (LSF) which is explained by\textsuperscript{3}. After Fourier transform of the Line Spread Function, it is found that\textsuperscript{3},

\[
G(f) = \frac{(\tau_b + \tau_t)\left(\omega\cos\text{e}ch(\omega) - e^{-\frac{1}{\Delta}}\omega\coth(\omega) - \Delta^{-1}e^{-\frac{1}{\Delta}}\right)}{\eta\Delta\left(1 - \frac{\tau_b}{\Delta}\right)}
\]

\[
- \left(\omega\cos\text{e}ch(\omega) - e^{-\frac{1}{\Delta}}\omega\coth(\omega) - \Delta^{-1}e^{-\frac{1}{\Delta}}\right)
\]

\[
\frac{\eta\Delta\left(1 - \frac{\tau_t}{\Delta}\right)}{\left(t_b^{-2} - \omega^2\right)}
\]

\[
\left(e^{-\frac{1}{\Delta}}\omega\cos\text{e}ch(\omega) - e^{-\frac{1}{\Delta}}\omega\coth(\omega) + \tau_t^{-1}e^{-\frac{1}{\Delta}}\right)
\]

\[
\frac{\eta\Delta\left(1 + \frac{\tau_t}{\Delta}\right)}{\left(t_t^{-2} - \omega^2\right)}
\]

\[
\left(e^{-\frac{1}{\Delta}} - e^{-\frac{1}{\Delta}}\right)
\]

where, \(\tau_b\) is normalized carrier lifetime for bottom electrode, \(\tau_t\) means normalized carrier lifetime for top electrode, \(\Delta\) is the normalized attenuation depth, \(\eta\) is quantum efficiency of the detector, \(\omega\) is the angular frequency and \(\omega = 2\pi f\), where, \(f\) is spatial frequency.

At zero spatial frequency, the expression for \(G(f=0)\) is\textsuperscript{2}:

\[
G(0) = \frac{(\tau_b + \tau_t)\left(1 - e^{-\frac{1}{\Delta}} - \Delta^{-1}e^{-\frac{1}{\Delta}}\right) - \tau_b\left(\tau_b - e^{-\frac{1}{\Delta}}\right)}{\eta\Delta\left(1 - \frac{\tau_b}{\Delta}\right)}
\]

\[
 \frac{\tau_t\left(e^{-\frac{1}{\Delta}} - 1 - e^{-\frac{1}{\Delta}}\right) - \tau_t\left(\tau_t - e^{-\frac{1}{\Delta}}\right)}{\eta\Delta\left(1 + \frac{\tau_t}{\Delta}\right)}
\]

\[
\frac{\tau_b\left(e^{-\frac{1}{\Delta}} - e^{-\frac{1}{\Delta}}\right)}{\eta\Delta\left(1 - \frac{\tau_b}{\Delta}\right)}
\]

Then, MTF due to bulk trapping\textsuperscript{4} is,

\[
MTF_{\text{trap}}(f) = \frac{G(f)}{G(0)}
\]

3. Data Acquisition

The dataset used in this study was formed from an experiment\textsuperscript{4} where fabrication of polycrystalline HgI\textsubscript{2} film was performed by real-time radiography using two low temperature deposition methods, Physical Vapour Deposition (PVD) and Particle-in-Binder (PIB) deposition. The experimenters performed PVD deposition in a vacuum reactor where high purity HgI\textsubscript{2} powder was evaporated and deposited on arrays. PIB deposition involves grains of purified HgI\textsubscript{2} crystals (\(\sim 6.36\) g cm\(^{-3}\)) mixed with a polymer binder material (\(\sim 1.05\) g cm\(^{-3}\)), with a composition ratio of 9 to 1 by weight for the two materials\textsuperscript{4}. In this study, we have worked on three publicly available prototypes of Poly-HgI\textsubscript{2} namely PVD #4, PVD #16 and PIB #2.\textsuperscript{4} The summary of three prototypes of HgI\textsubscript{2} used in our study is given in Table 1.

| Prototype code | Deposition method | Thickness (µm) |
|----------------|------------------|----------------|
| PVD#4          | PVD              | 210            |
| PVD#16         | PVD              | 280            |
| PIB#2          | PIB              | 615            |

Table 1. Summary of information related to the details of the polycrystalline HgI\textsubscript{2} detector for each of the prototype arrays evaluated in this study.
4. Result and Discussion

Firstly, numerical values of pre-sampled MTF from the published paper were extracted and the experimental curves were re-generated for the stated prototypes of poly-HgI$_2$. Figure 1 shows the re-generated experimental curves.

After that the MTF model was employed for all the three prototypes of poly-HgI$_2$. Simulation was performed for obtaining theoretical curves for Modulation Transfer Function. The aim is to fit curve from theoretical model with the experimental data. For the simulation of PVD #4 detector thickness is 210 µm. By varying electric field, we have seen that the best fitting occurs at electric field strength of .2V µm$^{-1}$. It’s notable that in case of PVD #4 (Figure 2), the chosen theoretical model of MTF gives exceptionally good results resembling the experimental data at high frequency region. For the simulation of PVD #16 (Figure 3), the detector thickness is 280 µm and the best fitting occurs at an electric field strength of .1V µm$^{-1}$. The simulation of PIB #2 (Figure 4), was performed at detector thickness 615 µm and electric field strength of .2V µm$^{-1}$. The theoretical model comprehensively satisfies the experimental results in the high frequency regions.

The X-ray sensitivity of pixelated X-ray detectors greatly depends on the mobility and lifetime product of charges that move towards the pixel electrodes and the extent of dependence increases with decreasing pixel per unit detector thickness. Table 2 shows the mobility-lifetime products and the electric field strengths for the best fitting of the experimental and theoretical curves.

![Figure 1. Regenerated experimental curves](image1.png)

![Figure 2. Fitting a curve for PVD #4 with thickness 210 µm and electric field strength .2 V µm$^{-1}$](image2.png)

![Figure 3. Fitting a curve for PVD #16 with thickness 280 µm and electric field strength .1 V µm$^{-1}$](image3.png)

![Figure 4. Fitting a curve for PIB #2 with thickness 615 µm and electric field strength .2 V µm$^{-1}$](image4.png)
The respective fitting errors of theoretical and experimental curves for the three prototypes are shown in Figure 5. It is evident that all the error patterns follow a definite trend. So there is a scope of introducing a fitting function to form an empirical model of MTF that will effectively reduce the fitting errors and give a comprehensive result for future researches. The formulation of such an empirical model calls for further study and researches.

A comparison between the average errors of \(^2\) and the current study are shown in Table 3. It is evident from Table 3 that the changes made in this study on the values of mobility lifetime product and photoconductor electric field strength yield significantly superior results than those of the paper\(^2\).

As mentioned in paper\(^2\), the dependence of dark current on exposure time and temperature\(^7\), carrier deep trapping\(^1\), K-fluorescence phenomena\(^1\) can also be invoked as possible reasons for the mismatches of simulation and experimental data. Furthermore, the primary photoelectron affects MTF performance greatly\(^1\). But, the effect of primary photoelectron was not taken into account in the model we used. In addition, there occurs some electrostatic blurring due to blocking layer in the photo-detector\(^8\). Thus, MTF gets reduced. Moreover, the blurring due to CCD readout\(^8\) is not considered in the model we have employed.

### 5. Conclusion

It is the primary focus of this study to shed light on the dependence of MTF on the photoconductor electric field strength which is not completely accounted for in the theoretical model. So the existing mismatches between the theoretical and the experimental results are to be expected. But we have also established by analysing the regularity among the error patterns that with the introduction of proper fitting functions, it is possible to derive an empirical model based on the theoretical model used in this study to fit the experimental results comprehensively. Since the improvement of the results in this study from that of the previous results is due to the change in values of mobility-lifetime product and photoconductor electric field strength, it can be inferred that, the aforementioned fitting functions for an empirical model will include mobility-lifetime product and electric field strength as independent variables. The derivation of the exact form of the required fitting functions and the complete empirical model calls for further studies. Such an empirical model will be helpful for future researches on HgI\(_2\) based flat panel x-ray image detectors.

### 6. References

1. Kabir MZ, Rahman MW, Shen WY. Modelling of detective quantum efficiency of direct conversion x-ray detectors incorporating charge carrier trapping and K-fluorescence. IET Circuits Devices Systems. 2011; 5(3):222–31.
2. Ashikuzzaman M, Ali J, Adib R, Hossain MM, Mahmood SAV. HgI₂ as x-ray imager: Modulation transfer function approach. International Journal of Modern Research Engineering Technology. 2016 Jul; 1(2):1–4.
3. Kabir MZ, Kasap SO. Modulation transfer function of photoconductive x-ray image detectors: effects of charge carrier trapping. Journal of Physics D: Applied Physics. 2003; 36:2352–8.
4. Du H, Antonuk LE, Mohri YE, Zhao Q, Su Z, Yamamoto J, Wang Y. Investigation of the signal behavior at diagnostic energies of prototype, direct detection, active matrix, flat-panel imagers incorporating polycrystalline HgI₂. Physics Medicine Biology. 2008; 53(5):1325–51.
5. Lubberts G. The line spread function and the modulation transfer function of x-ray fluorescent screen-film systems—problems with double-coated films. American Journal of Roentgenology. 1969; 105(4):909–17.
6. Whited RC, Berg LVD. Native defect compensation in HgI₂ crystals. IEEE Transaction on Nuclear Science. 1977; 24(1):165–7.
7. Zentai G, Partain L, Pavlyuchkova R, Proano C, Breen BN, Taieb A, Dagan O, Schieber M, Gilboa H, Thomas J. Mercuric iodide medical imagers for low exposure radiography and fluoroscopy. Proceedings of SPIE.5368; 2004. p. 200–10.
8. Hunter DM, Belev G, DeCrescenzo G, Kasap SO, Mainprize JG, Rowlands JA. The dependence of the modulation transfer function on the blocking layer thickness in amorphous selenium x-ray detectors. Medical Physics. 2007; 34(8):3358–73.