Novel Radiation Detector Capable of Measuring the Energy of Individual X-ray Photons at High Flux Rates to Advance X-ray Imaging Technologies for Cancer

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Quarterly Seminar 7 May 2014

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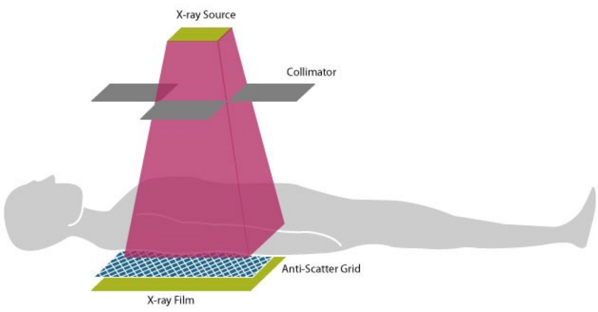
Outline

- Background
- Conventional & Photon Counting Detectors
- HEMT devices & Novel x-ray detector proposal
- MC simulations
- Device simulations
- Results
- Future Work
- Conclusions

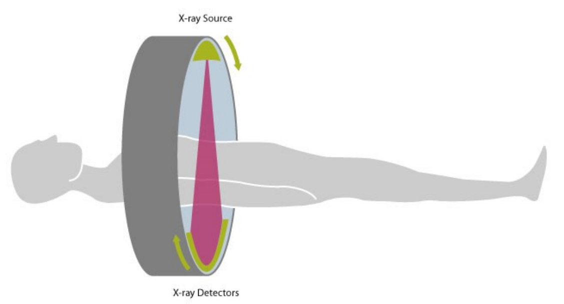
X-rays in Medical Imaging

Since their discovery in 1895 by Wilhelm C. Röntgen, x-rays have been playing a critical role in medical imaging.

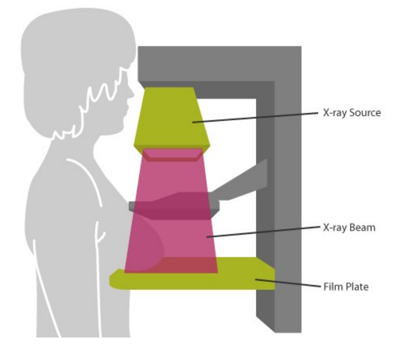
Radiography



CT



Mammography



Angiography

Fluoroscopy

Images from medicalradiation.com

Limitations

Current CT and x-ray imaging technologies there are four major limitations:

- The contrast between different soft tissues is often insufficient;
- Images are not tissue-type specific (different tissue types can appear with similar pixel values);
- CT scanning is a relatively high-dose procedure [1];
- Gray-scale pixel values of CT images, which should be linear attenuation coefficients, are not quantitative but qualitative.

These limitations result from or are made worse by the **conventional energy integrating detectors** used in CT scanners and x-ray systems. [2]

[1] F. A. Mettler, et al. J. Radiol. Prot. 20,353–359 (2000)
[2] K. Taguchi et al. Med. Phys. 40, 100901 (2013)

Conventional Integrating Detectors

■ The conventional integrating detectors measure the energy-integrated signals of x-ray photons

- losing all of the energy-dependent information.

■ Also integrating detectors

- add electronic noise and Swank noise [3]
- weight lower energy photons less, which carry larger contrast between tissues than higher energy photons [2].

▸ This results in increased noise and decreased contrast.

■ Dual-energy CT imaging [4] can provide tissue-specific images. But

- Cross-talk between the high & low energy images
- Number of resolvable basis functions for material decomposition is limited to two.
  A third basis function is required to identify contrast media with high atomic numbers

▸ Desirable to measure the transmitted x-ray photons in more than two energy windows [2].

[2] K. Taguchi et al. , Med. Phys. 40, 100901 (2013)
[3] R. K. Swank, J. Appl. Phys. 44,4199–4203(1973)
[4]R. E. Alvarez et al., Phys. Med. Biol. 21,733–744(1976)
[5]L. Yu et al., Med. Phys. 36,1019–1024(2009)

Photon Counting

■ Photon counting detectors with energy resolving capabilities based on pulse height analysis have been developed for medical x-ray imaging.

- Potential to improve the four major limitations is discussed earlier [2].

■ Photon counting, energy resolving x-ray detectors have become an active area of research:

- **Reduced dose** while maintaining good contrast
- **Compositional analysis** through multiple basis function material decomposition,
- **Contrast enhancement** through spectroscopic x-ray imaging of metal nanoparticles [6]

Sensors based on CdTe, CZT, Si are available. Advanced research developments based on HgI_2 and GaAs exist.

[2] K. Taguchi et al. , Med. Phys. 40, 100901 (2013)
[6] Barber et al. Proc. of SPIE, Volume 8143,81430J, 8 pp. (2011)

Photon Counting (II)

■ However there are still problems with the new technology that hamper clinical use:

- insufficient high count rate capabilities of the detectors and readout electronics [7-9]
- intensity-dependent image artifacts associated with defects in CZT and CdTe crystals [10] and
- limited energy resolution associated with hole trapping and leakage current in CZT and CdTe materials [11-14]

[7] Barber W C et al. SPIE 7258 2401-9 (2009)
[8]Shikhaliev P M, Phys. Med. Biol. 53 1475-95 (2008)
[9]Taguchi K et al. Med. Phys. 37 3957-69 (2010)
[10]Shikhaliev P M, Phys. Med. Biol. 54 4971-92 (2009)
[11] Cajipe V B et al. IEEE Nucl. Sci. Symp. V7 pp 4548-51 (2004)
[12] Szeles C et al. IEEE Trans. Nucl. Sci. 54 1350-8 (2007)
[13]Schlomka J P et al. Phys. Med. Biol. 53 4031-47 (2008)
[14] Shikhaliev P M, Phys. Med. Biol. 53 5595-613 (2008)

HEMT-based detector

- A novel HEMT-based photon-counting energy-resolving x-ray is proposed [15]

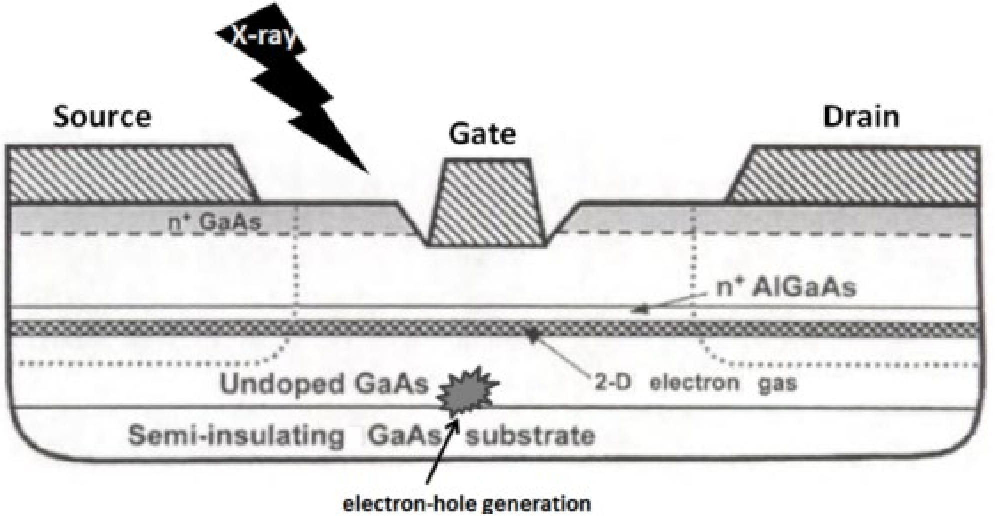
- HEMT (High Electron Mobility Transistor) is a transistor incorporating a junction between two materials with different band gaps as the channel instead of a doped region.

- Field-effect modulation of high-mobility two-dimensional electron gas (2DEG)

- It offers a combination of **low noise** figure combined with the **very high frequency operation**.

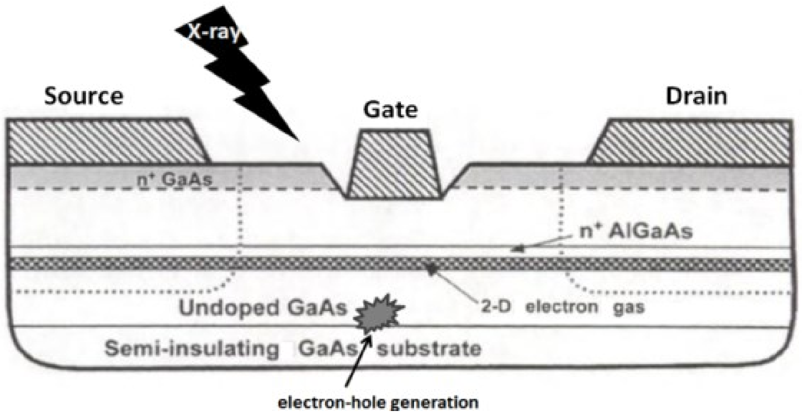
- Used in ultra-fast switches for telecom, and low noise amplifier electronics,
  - but to date, no one has considered these devices for use in x-ray detection.

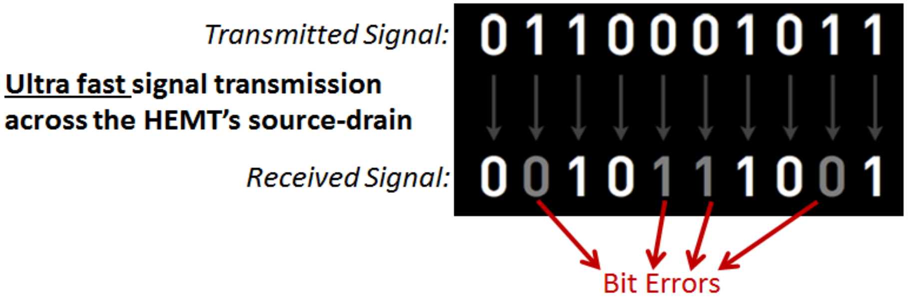
- HEMT's unique super-high bandwidth (BW) (up to 600GHz has been achieved [15])



[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013
[16] Bollaert, IEEE EDL, vol.23, no.2, pp.73,75, Feb. 2002

Digital Detection





bit error rate

$t_{error\text{-}free}$ vs. $t_{erroneous}$ transmission

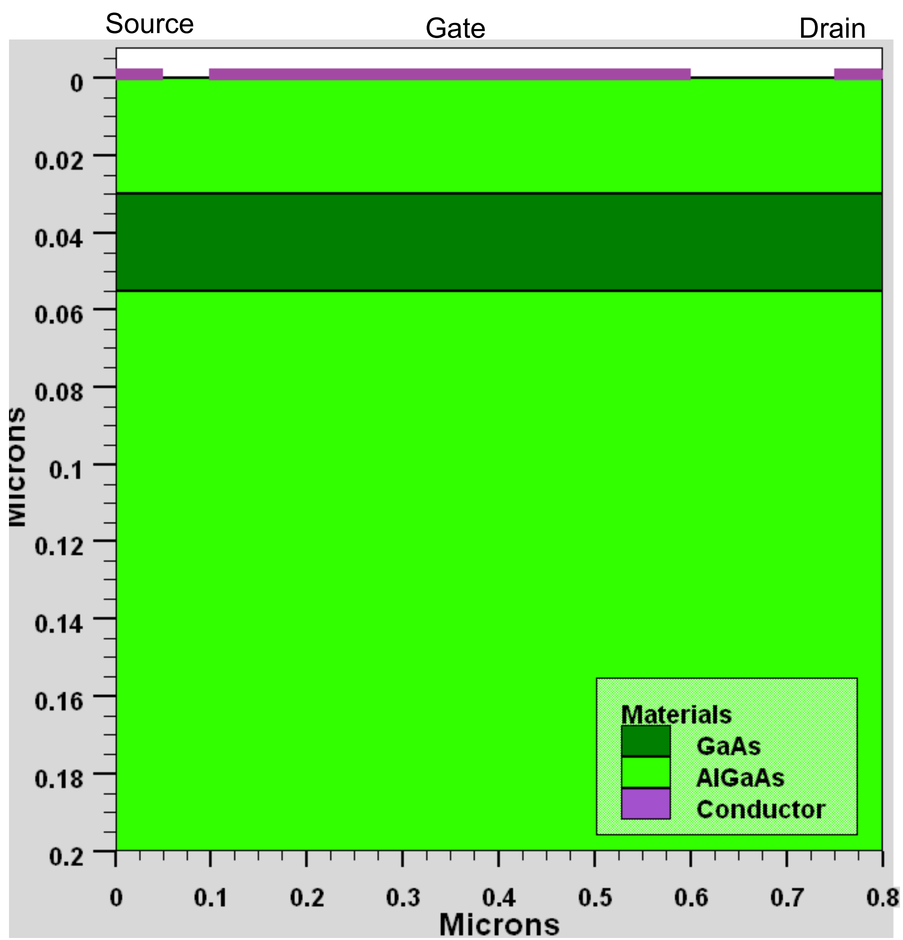
⇩

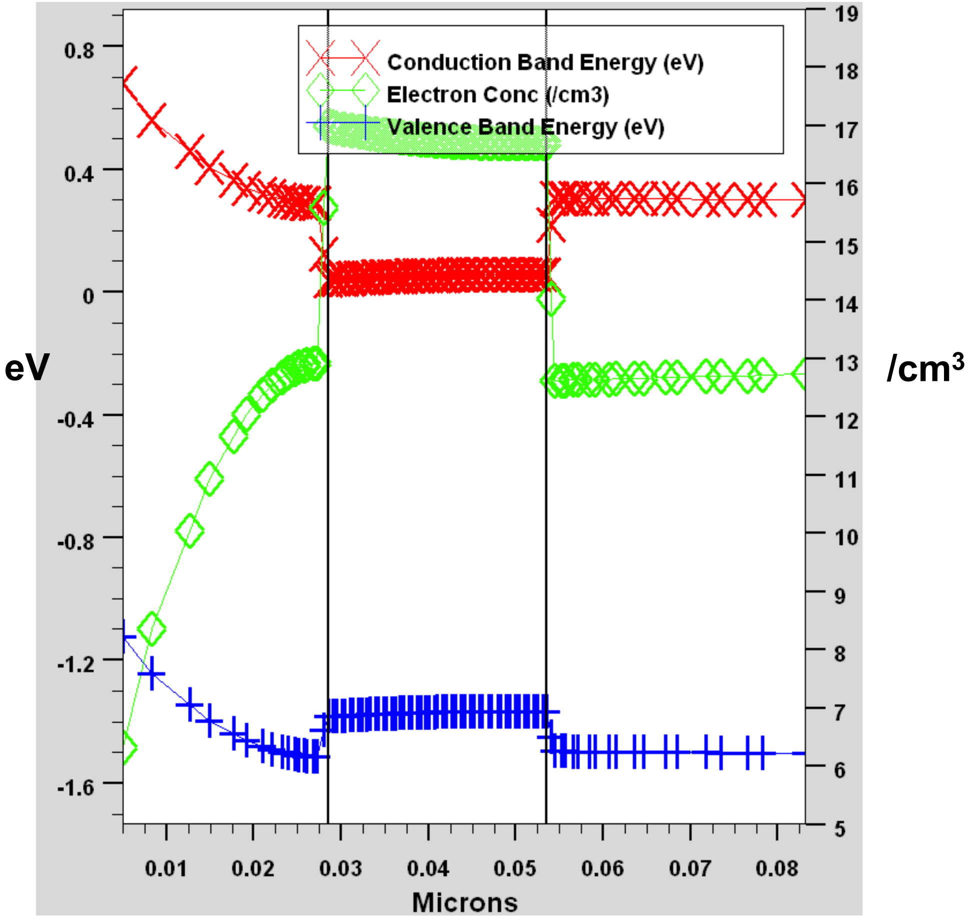
Measure the energy of individual photon at high flux rates

[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013 (Oral Presentation)

Basic AlGaAs/GaAs HEMT

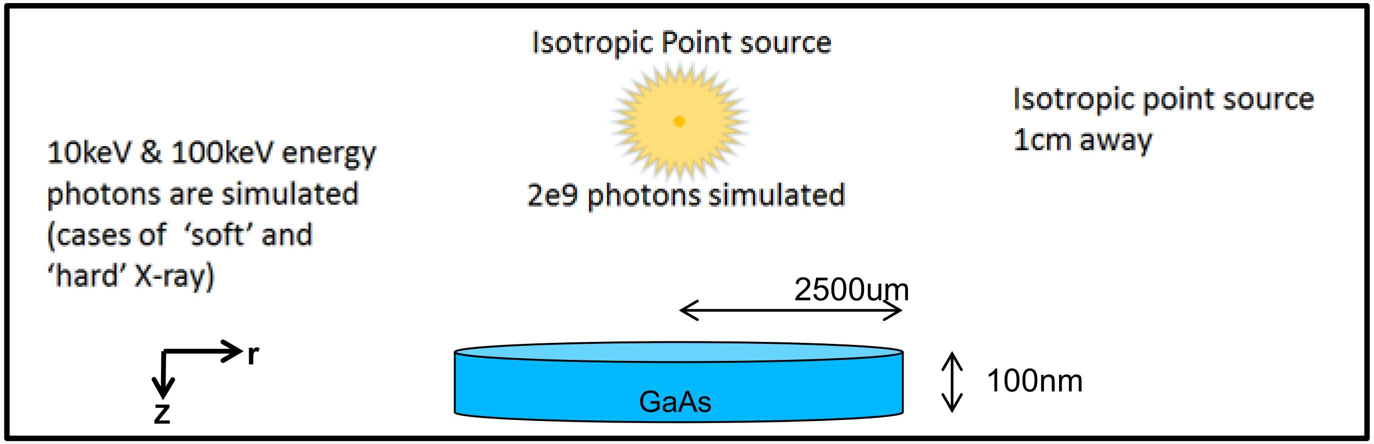
A Basic HEMT structure





[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013 (Oral Presentation)

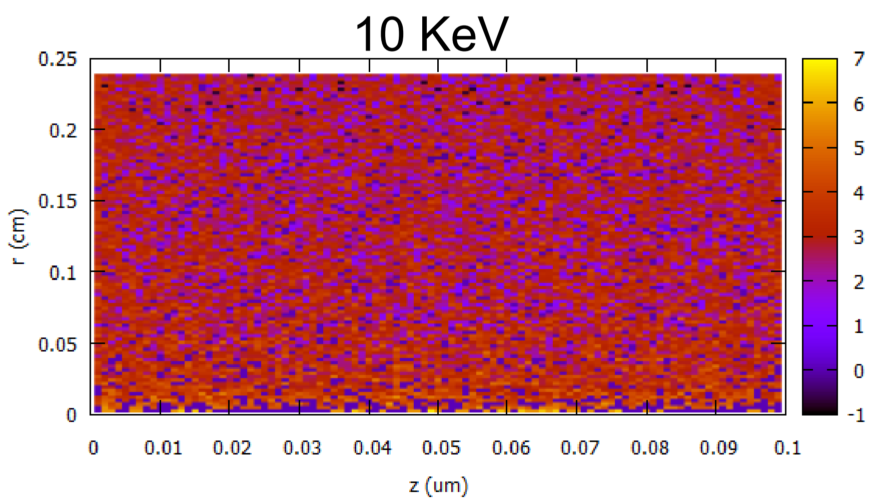
MC Simulations



Monte Carlo simulations done with PENELOPE [16] to simulate the charge deposition profile within the material of interest

[16] F.Salvat, J.M. Fernandez-Varea, E.Acosta and J.Sempau, OECD/NEA 5-7 November 2001

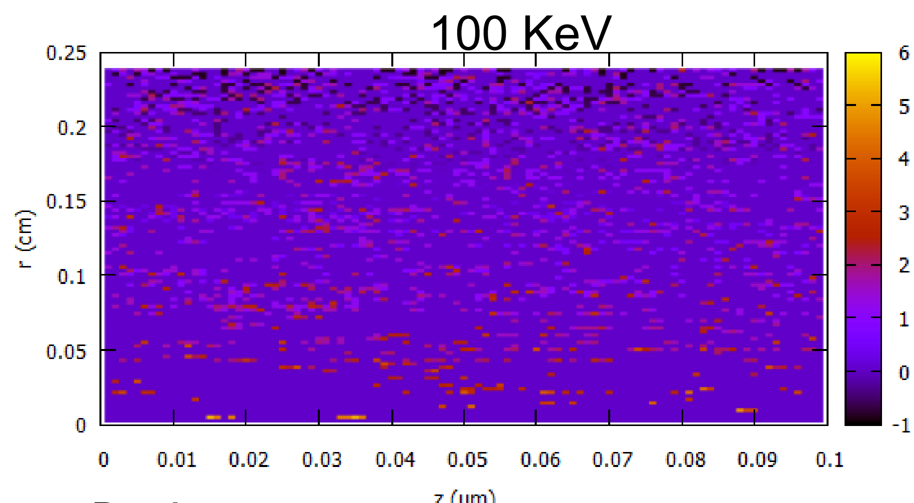
Deposited charge distribution (log(1+charge density (e/cm^3)))



Results:
Simulated primary particles .... 2.00E+09

Absorbed primary particles .... 5.34E+04

Absorption fraction .... 2.67E-05 +- 3.5E-07



Results:
Simulated primary particles .... 2.00E+09

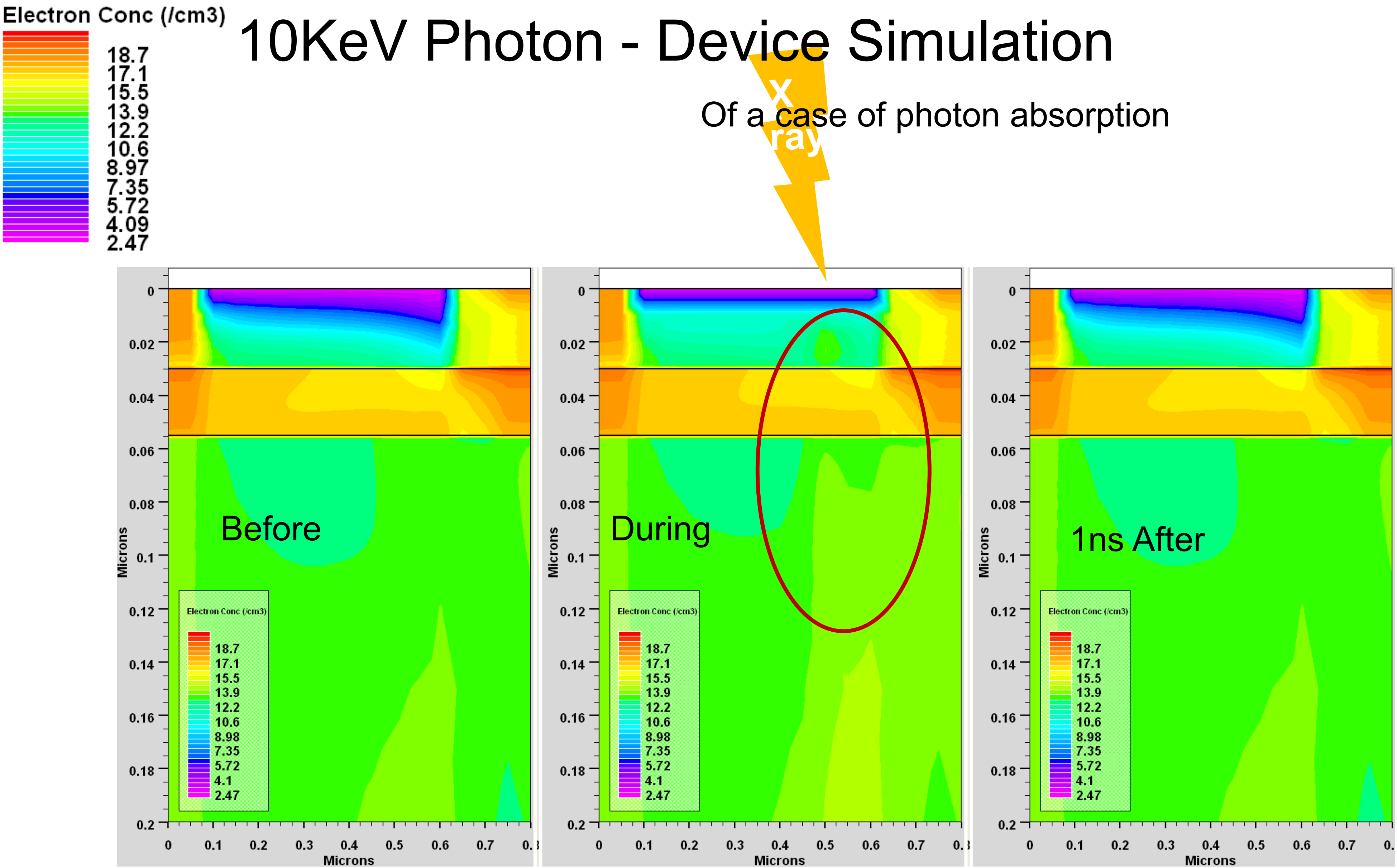
Absorbed primary particles .... 5.67E+02

Absorption fraction .... 2.83E-07 +- 3.6E-08

[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013 (Oral Presentation)

10KeV Photon - Device Simulation

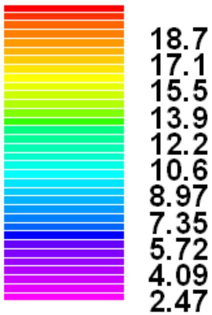
Of a case of photon absorption

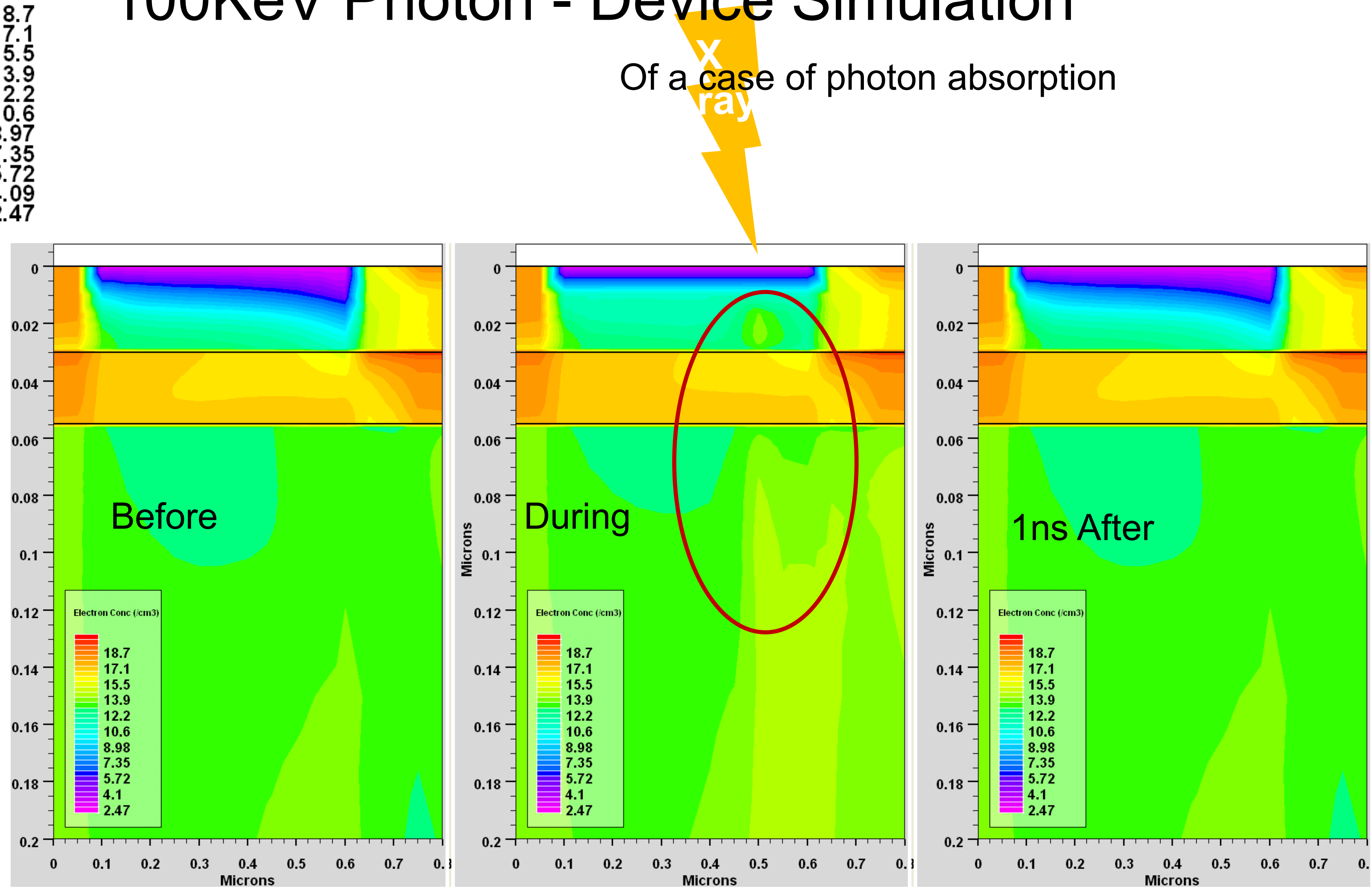


[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013 (Oral Presentation)

100KeV Photon - Device Simulation

Of a case of photon absorption

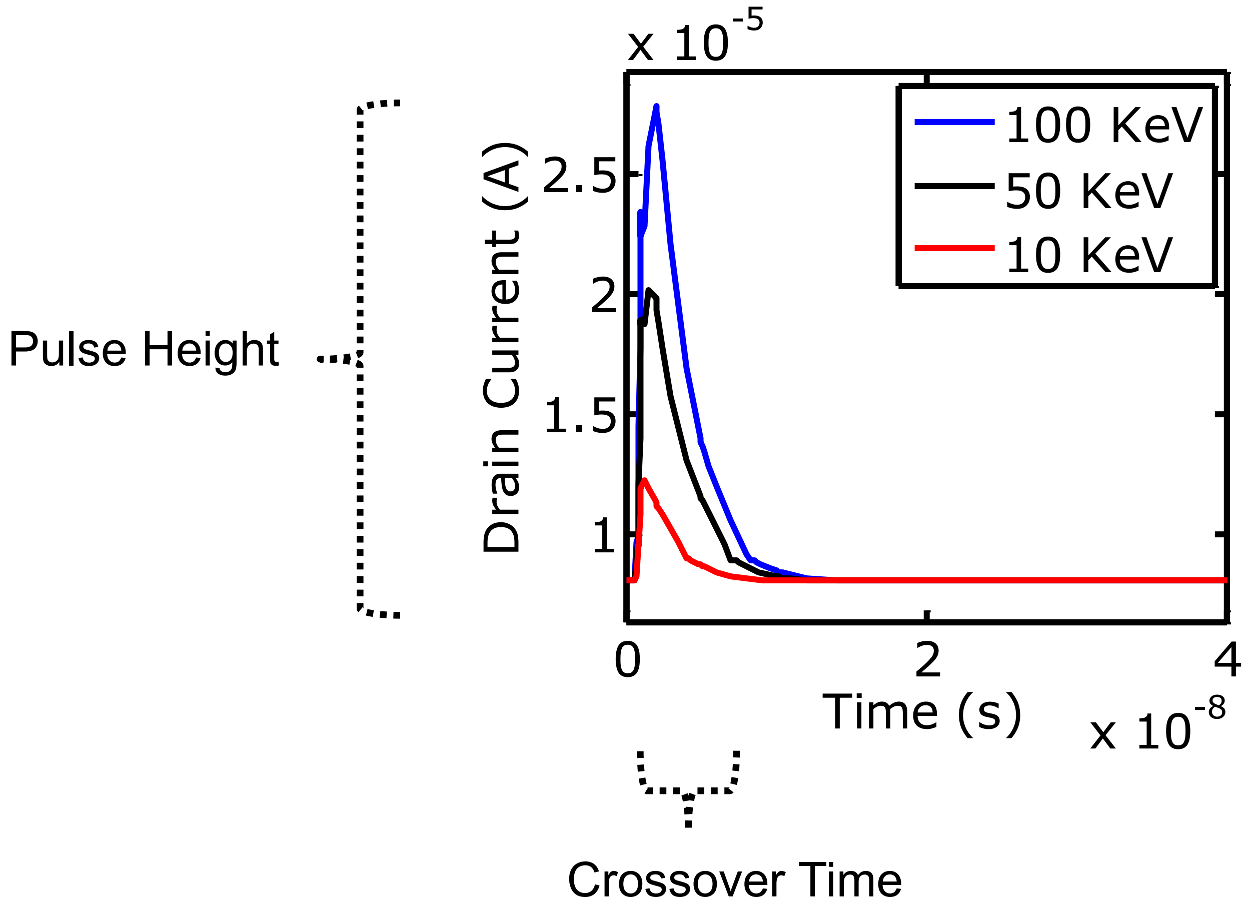




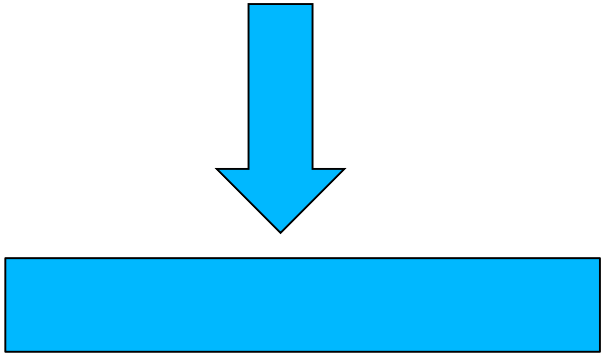
[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013 (Oral Presentation)

Detection

Simulation of the transient drain current from 10KeV, 50KeV and 100KeV photon absorption cases



Utilisation of pulse height and/or pulse width information



[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013 (Oral Presentation)

Future Work

- Experiments with the off-the-shelf devices

- Optimizing the device structure further

- Simulations of the optimised devices

GOAL:

- Detection of individual photons

- Operation in energy resolving manner

- Ultra-fast Operation

Conclusions

- We predict that the proposed HEMT-based x-ray detector can detect individual photons in an energy resolving manner

- Thanks to the very high frequency operation of the HEMT device, theoretically ultra-fast operation possible

- In this initial work we simulated commercially available device parameters, and due to the extremely thin (~100 nm) absorption region, the presented absorption probabilities are extremely low

- We hypothesize that much thicker, higher Z, and higher density custom engineered devices made for the detection purpose would have a much higher sensitivity, and detection efficiency.

Acknowledgments

Stanford Cancer Imaging Training (SCIT) Program

GE Healthcare

Stanford School of Medicine Dean's Postdoctoral Fellowship

IEEE MIC Trainee grant