

HEMT-based photon-counting energy-resolving x-ray detector

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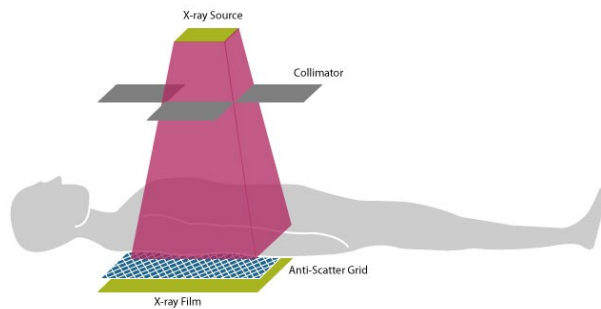
Outline

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

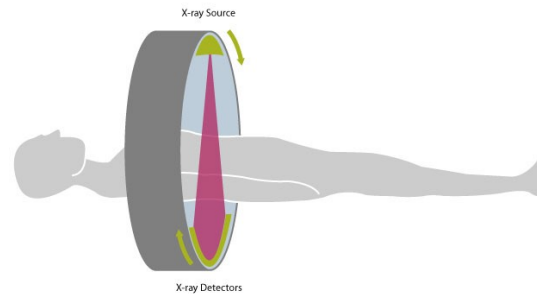
X-rays in Medical Imaging

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

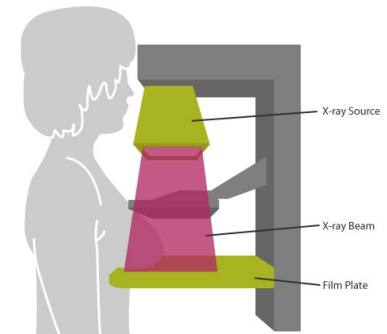
Radiography



CT



Mammography



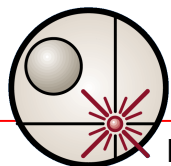
Angiography



Fluoroscopy



Images from medicalradiation.com



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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 HgI₂ 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)

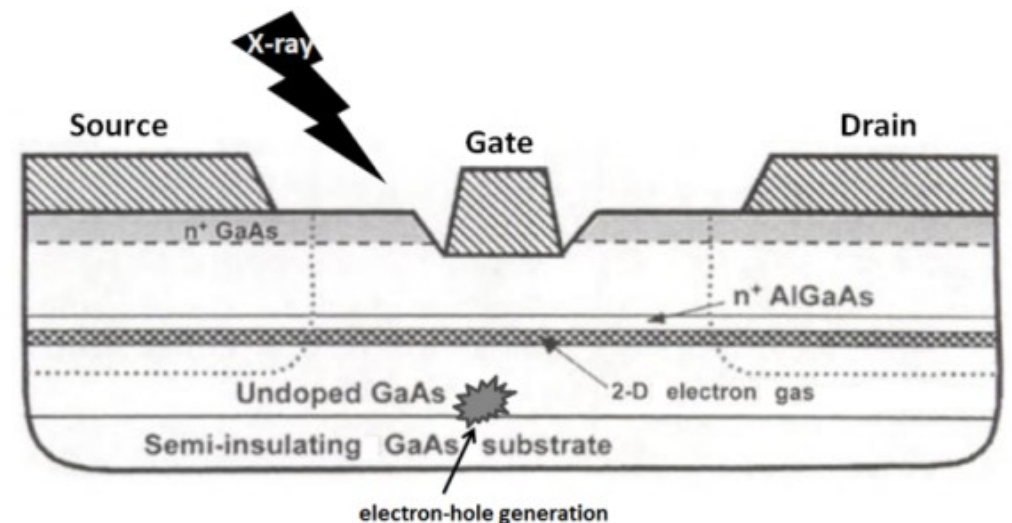
[12] Szeles C et al. IEEE Trans. Nucl. Sci. 54 1350-8 (2007)

[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

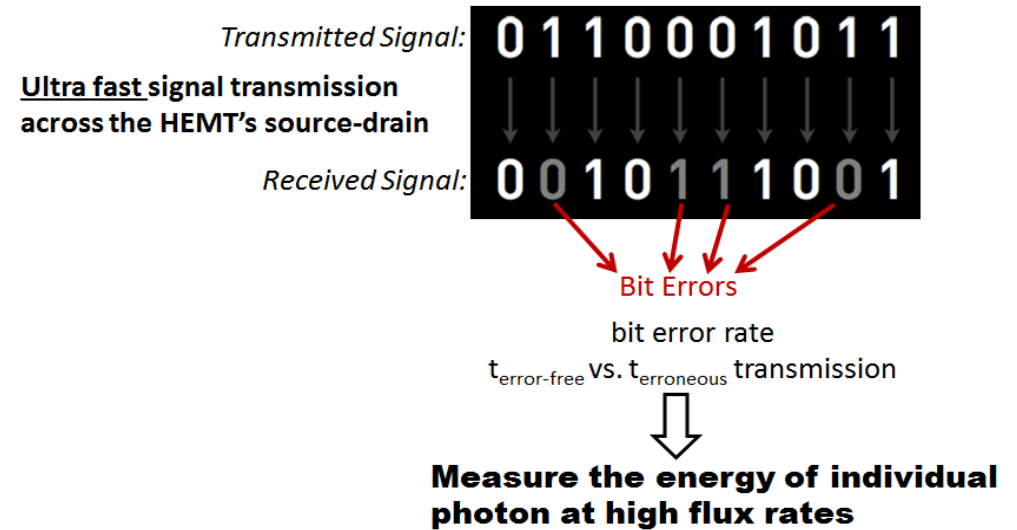
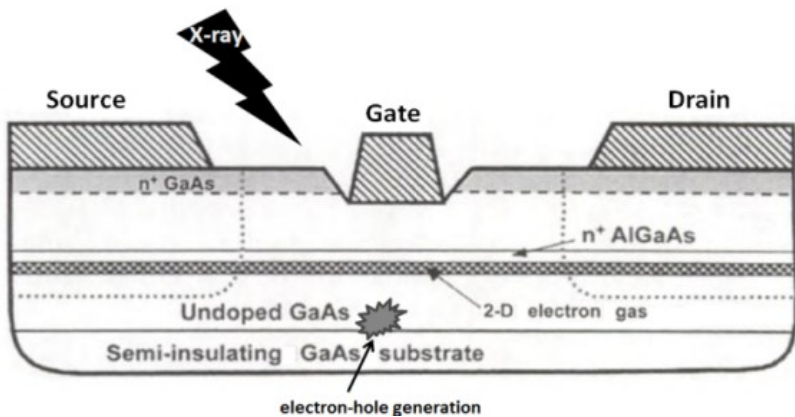
- A novel HEMT-based photon-counting energy-resolving x-ray is proposed [15]
- HEMT (High Electron Mobility Transistor) is a transistor incorporating a junction between two materials with different band gaps as the channel instead of a doped region.
- Field-effect modulation of high-mobility two-dimensional 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

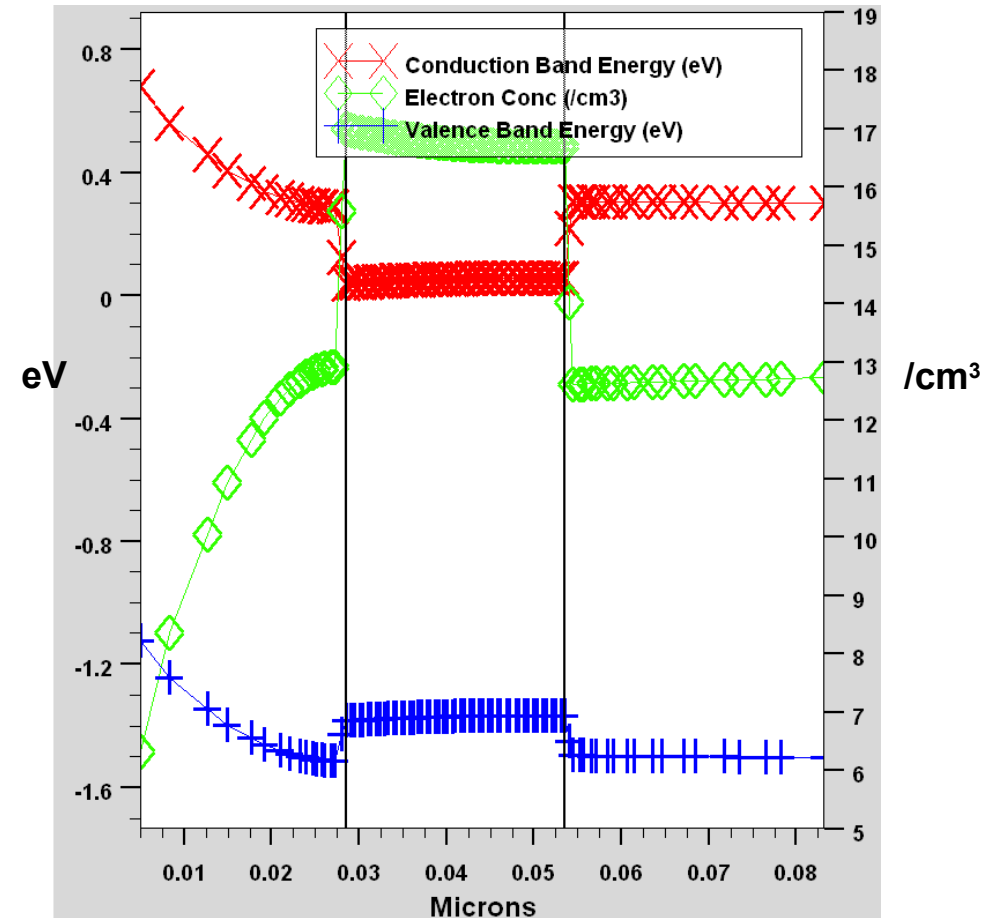
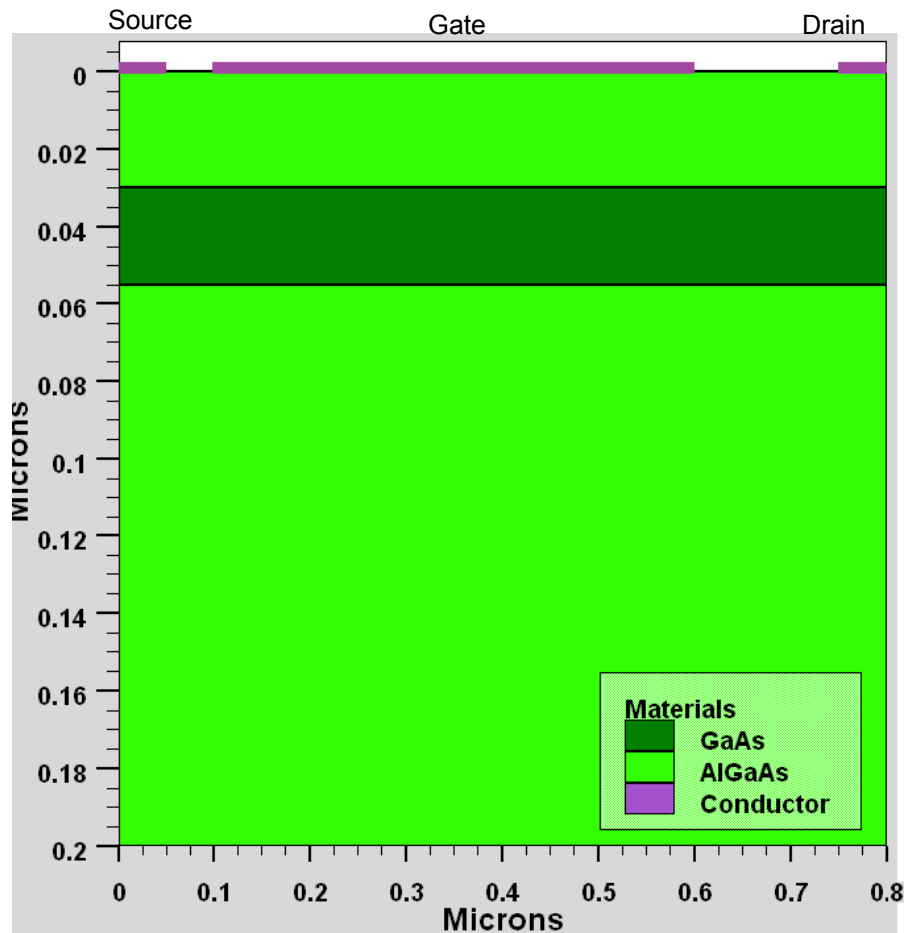
Digital Detection



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

Basic AlGaAs/GaAs HEMT

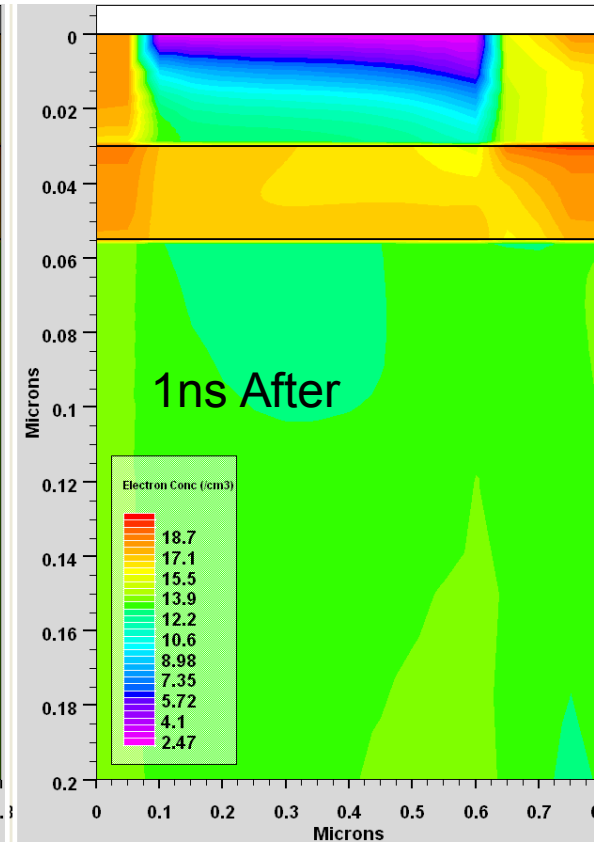
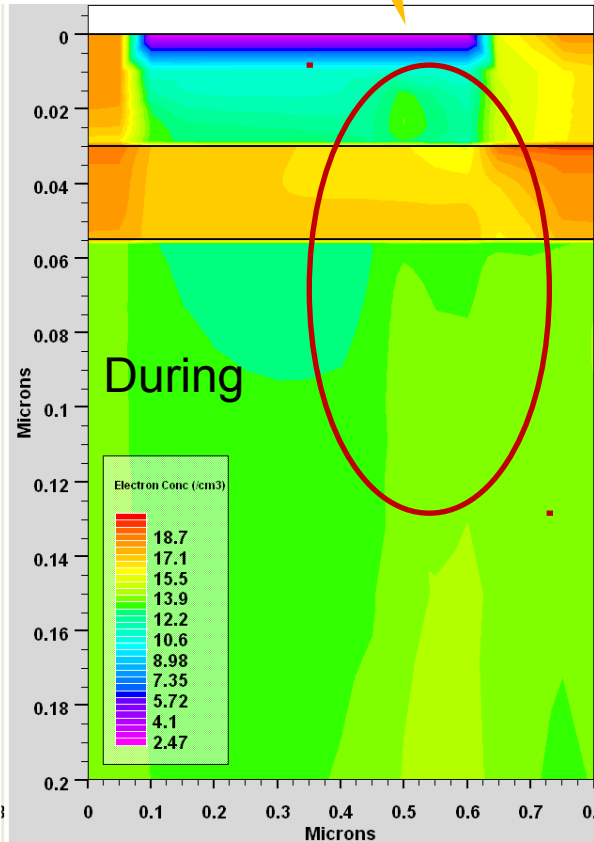
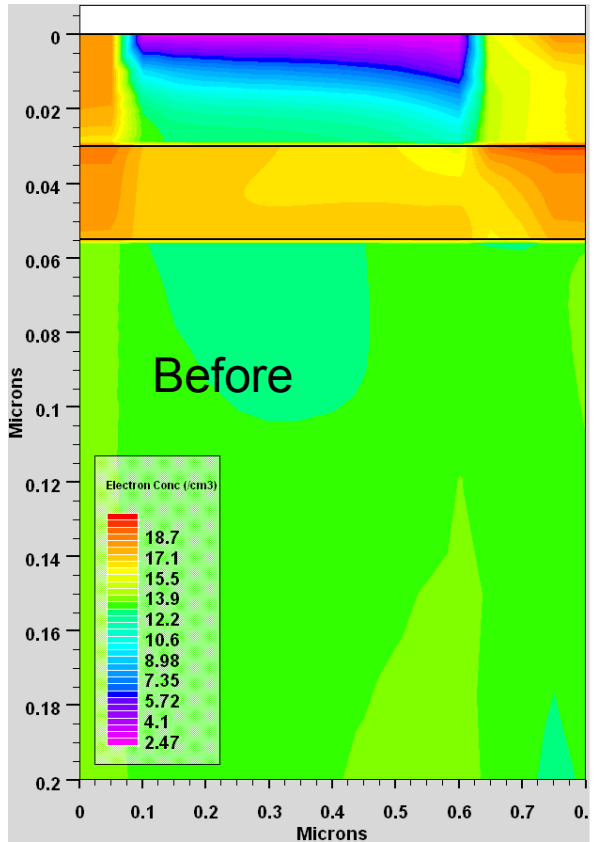
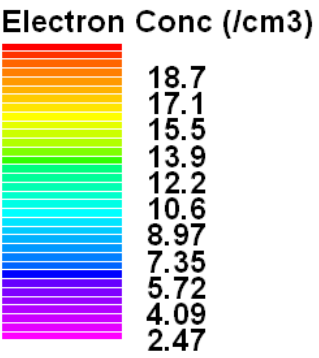
A Basic HEMT structure



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

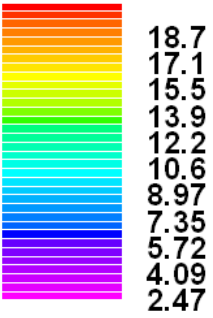
10KeV Photon - Device Simulation

Of a case of photon absorption



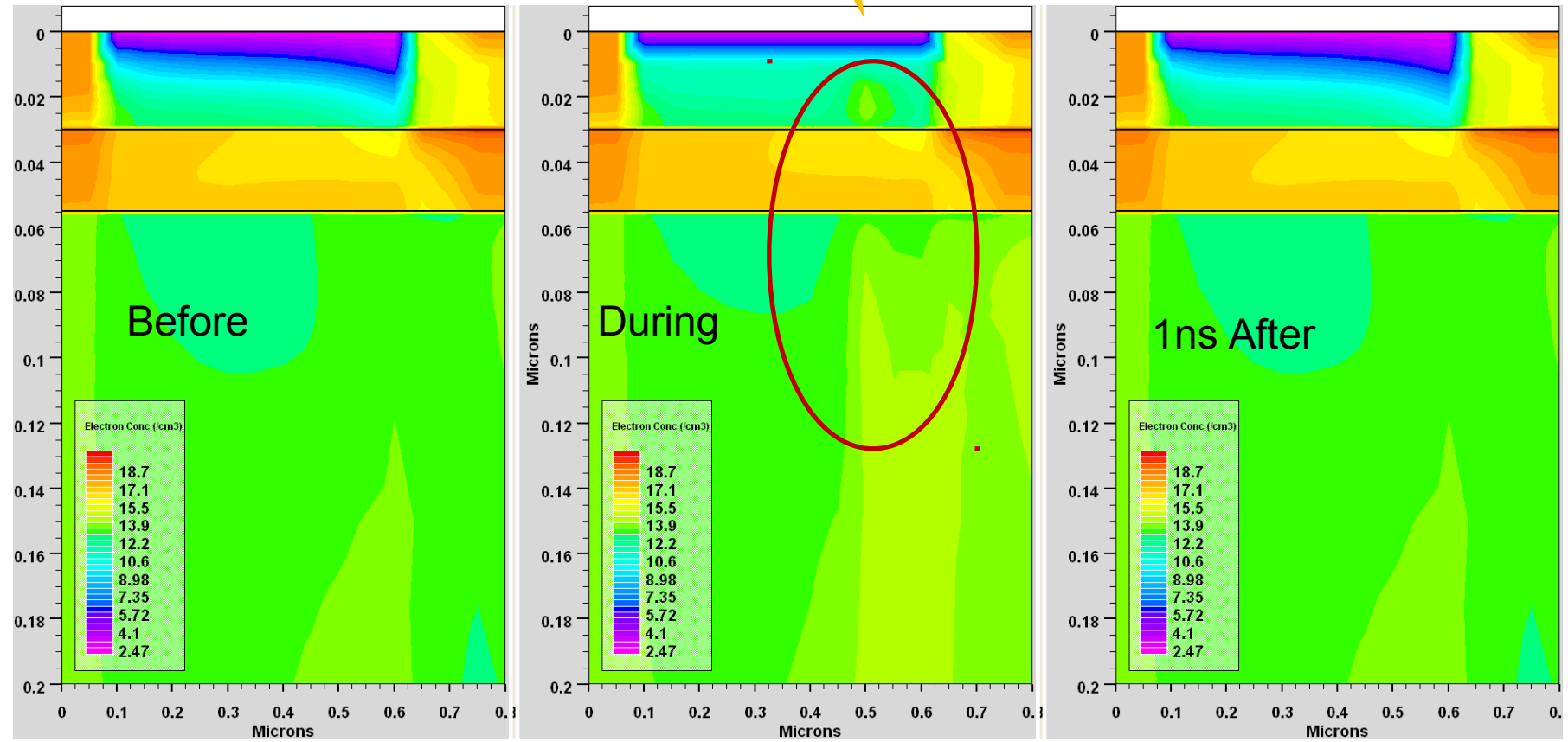
[15]M. G. Ertosun, C. S. Levin, IEEE NSS/MIC, October 2013

Electron Conc (/cm³)



100KeV Photon - Device Simulation

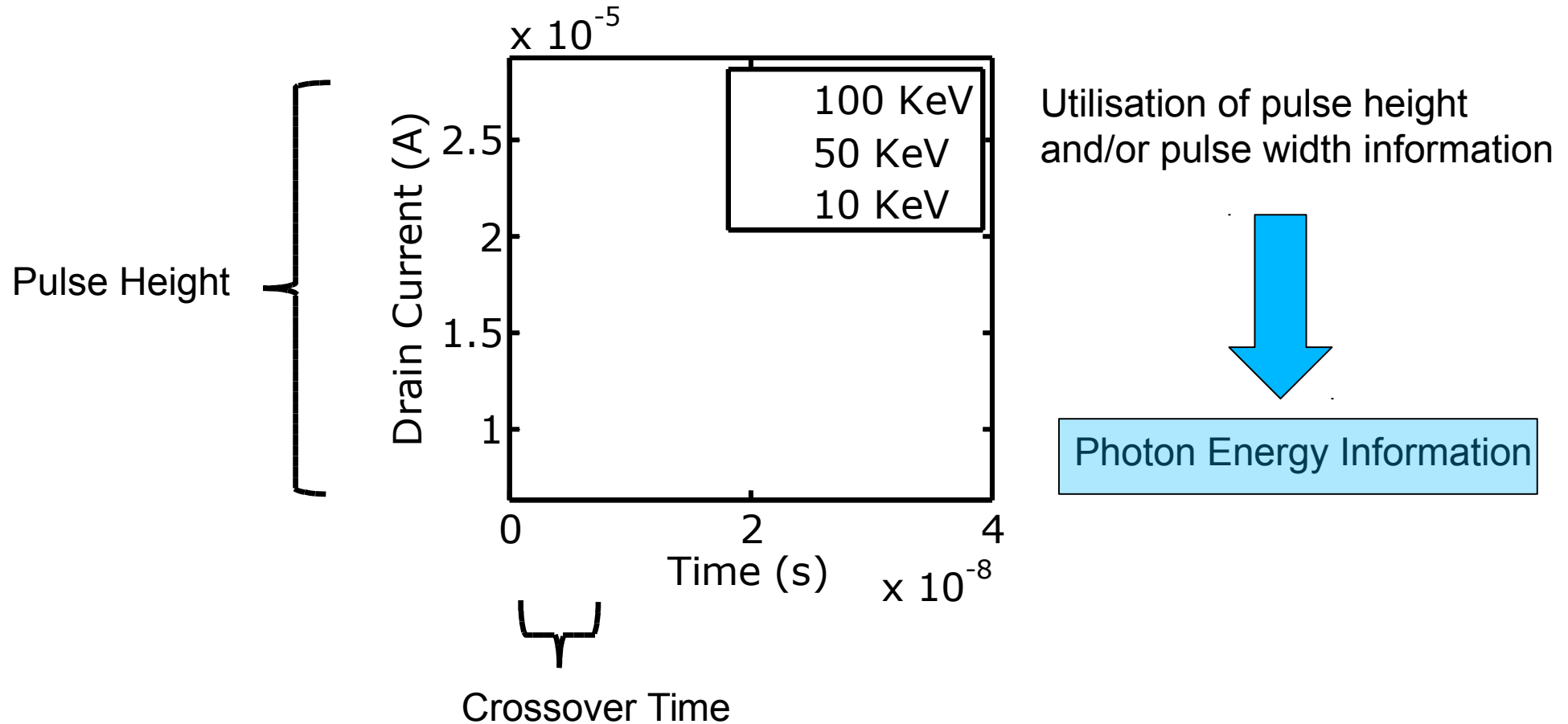
Of a case of photon absorption



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

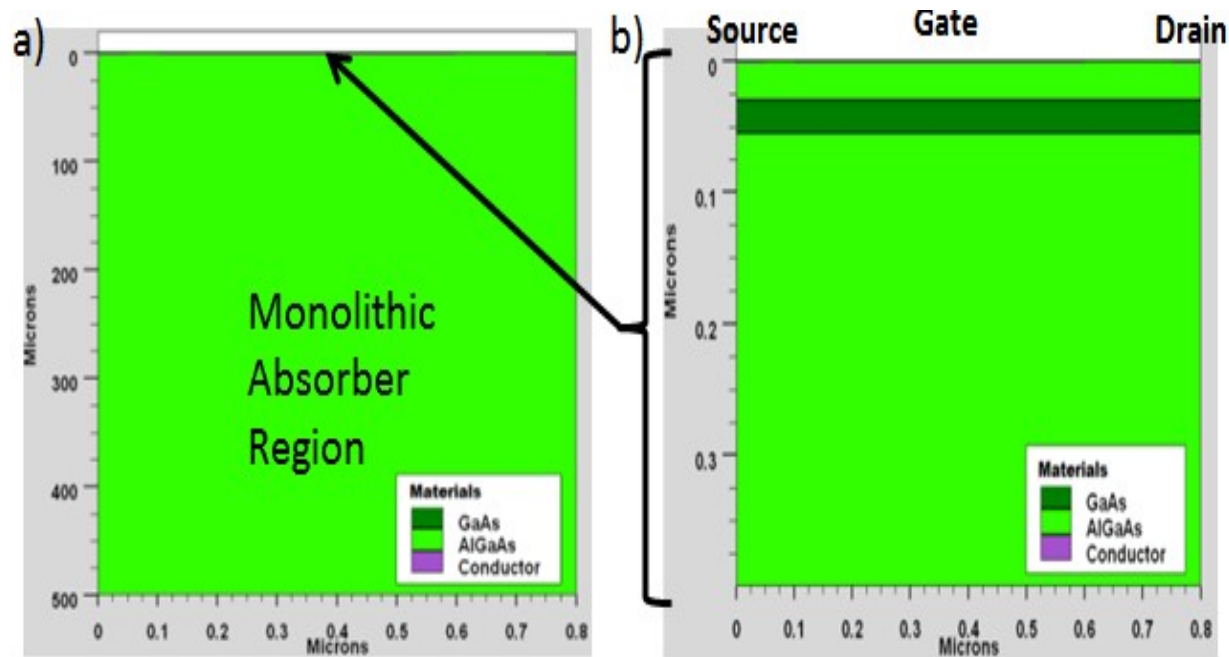
Detection

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

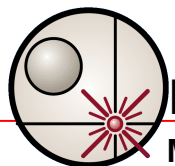


Improved Sensitivity

Improving sensitivity by incorporating an absorber region



[15]M. G. Ertesun, C. S. Levin, IEEE NSS/MIC, November 2014



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from the original talk.

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
- Initially we simulated commercially available device parameters, and due to the extremely thin (~100 nm) absorption region, the absorption probabilities were extremely low
- We then studied a structure with a thicker absorption layer so as to increase the probability of interaction
- The resulting device with improved sensitivity can detect individual photons along with their energy information

Acknowledgments



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IEEE MIC Trainee grant 2014

