PROTOTYPES OF SELF-POWERED RADIATION DETECTORS EMPLOYING INTRINSIC HIGH-ENERGY CURRENT (HEC) (POSTPRINT)

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Contract No. FA8051-15-P-0010

January 2016

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Purpose: The authors experimentally investigate the effect of direct energy conversion of x-rays via self-powered Auger- and photocurrent, potentially suitable to practical radiation detection and dosimetry in medical applications. Experimental results are compared to computational predictions. The detector the authors consider is a thin-film multilayer device, composed of alternating disparate electrically conductive and insulating layers. This paper focuses on the experiments while a companion paper introduces the fundamental concepts of high-energy current (HEC) detectors.

METHODS: The energy of ionizing radiation is directly converted to detector signal via electric current induced by high-energy secondary electrons generated in the detector material by the incident primary radiation. The HEC electrons also ionize the dielectric and the resultant charge carriers are selfcollected due to the contact potential of the disparate electrodes. Thus, an electric current is induced in the conductors in two different ways without the need for externally applied bias voltage or amplification. Thus, generated signal in turn is digitized by a data acquisition system. To determine the fundamental properties of the HEC detector and to demonstrate its feasibility for medical applications, the authors performed planar geometry composed of multilayer microstructures. Various detectors with up to seven conducting layers with different combinations of materials (250 μm Al, 35 μm Cu, 100 μm Pb) and air gaps (100 μm) were exposed to nearly plane-parallel 60-120 kVp x-ray beams. For the experimental design and verification, the authors performed coupled electron-photon radiation transport computations. The detector signal was measured using a commercial data acquisition system with 24 bits dynamic range, 0.4 fC sensitivity, and 0.9 ms sampling time.

RESULTS: Measured signals for the prototype detector varied depending on the number of layers, material type, and incident photon energy, and it was in the range of 30-150 nA/cm² for unit air kerma (1 Gy), which is viable for practical applications. The experiments had an excellent agreement with the computations. Within the examined range of 60-120 kVp, the energy dependence of the HEC (normalized to the x-ray tube output) was relatively small.

CONCLUSIONS: Based on the experimental results for 100 ms sampling time, it would be possible to measure the time dependence of x-ray beams for x-ray tube current of 0.1 mA or higher. Significant advantages of the HEC device are that generation of its signal does not require external power supply, it can be made in any size and shape, including flexible curvilinear forms, and it is inexpensive. It remains to be determined, which of the potential applications in medical dosimetry (both in vivo and external), or radiation protection would benefit from such selfpowered detectors.

AbSTRACT

The authors experimentally investigate the effect of direct energy conversion of x-rays via self-powered Auger- and photocurrent, potentially suitable to practical radiation detection and dosimetry in medical applications. Experimental results are compared to computational predictions. The detector the authors consider is a thin-film multilayer device, composed of alternating disparate electrically conductive and insulating layers. This paper focuses on the experiments while a companion paper introduces the fundamental concepts of high-energy current (HEC) detectors.

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Subject Terms: Auger, direct conversion, electron current, high-energy current, radiation detection, self-powered, thin-film
Prototypes of self-powered radiation detectors employing intrinsic high-energy current
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Citation: Medical Physics 43, 16 (2016); doi: 10.1118/1.4935532
View online: http://dx.doi.org/10.1118/1.4935532
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Prototypes of self-powered radiation detectors employing intrinsic high-energy current

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(Received 14 July 2014; revised 22 October 2015; accepted for publication 29 October 2015; published 15 December 2015)

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Key words: radiation detection, electron current, Auger, photocurrent, self-powered, thin-film
1. INTRODUCTION

Electrons set in motion by incident ionizing radiation possess high kinetic energies and high velocities, and therefore they can form a high-energy current (HEC). A priori, as proposed by Zygmanski and Sajo, high-energy current could be employed for signal formation in x-ray and charged particle devices (detectors, sensors, converters, or transformers), which may be suitable for kV dosimetry or beam monitoring. A notable feature of a device operating on this principle is that it is selfpowered, in that it does not require external voltage bias to induce and collect a signal proportional to the incident radiation. Hitherto, the application of similar high-energy electron currents has been confined to in-core neutron flux detectors in nuclear reactors and Compton detectors. Electron current formed by photoelectrons and especially Auger electrons has received much less attention, and it has been investigated mostly in macroscopic geometries in defense and space applications. Although it has been considered in relation to Compton or in-core neutron detectors, its potential has not been fully utilized.

The device considered here is a multilayer (or periodic) microstructure or nanostructure composed of alternating high atomic number (high-Z) and low atomic number (low-Z) conducting layers separated by a low-Z dielectric, such as shown in Fig. 1. The ideal dielectric for HEC mechanism is a void (vacuum) because it does not attenuate the high-energy current, while it provides electric insulation between the conductors. Low-density gas or gas mixture, such as air, is an acceptable alternative. For thin layers, it may be possible to use a low density solid dielectric, e.g., SiO₂. In the present proof-of-principle study, we use air as the low-Z dielectric, copper (Cu) and lead (Pb) as high-Z materials, and aluminum (Al) as the low-Z conductor.

Details of the HEC concept are discussed by Zygmanski and Sajo. Briefly, formation and utilization of HEC are most efficient when the incident x-rays interact with high-Z materials by photoelectric absorption, resulting in photoelectrons, Auger electrons, and fluorescent photons. If the material is thick, there is a substantial attenuation of both the primary incident radiation and the secondary electrons within the material itself, leading to energy deposition without commensurate signal formation. If the material is thin compared to the range of the secondary electrons, it becomes a significant source of leakage electrons (per unit absorbed dose), which can be collected by an adjacent medium- or low-Z conductor electrode. For Auger electrons, the escape depth is a few nanometers to micrometers, thus their role in the generation of HEC is non-negligible only for a series of very thin layers of high-Z materials as opposed to a single but equivalent-volume layer. The leakage of photoelectrons and Auger electrons from high-Z to low-Z materials and the subsequent signal generation by conduction or low-energy electrons are greatest when there is a large disparity between their atomic numbers. Low-energy current (LEC) induced by HEC in the external circuit is the electric current that constitutes the signal in the device. In the case of nonvacuum media high-energy leakage electrons from the conducting layers generate low-energy charge carriers in the dielectric. Therefore, the detector signal has two components: (a) the direct contribution from the high-energy leakage current itself, and (b) the indirect contribution from the ionization charges produced in the dielectric by the HEC. Transport and selfcollection of the latter charge carriers by the electrodes occur due to the internal electric field formed by the Fermi potentials of the disparate material electrodes.

In medical therapeutic and imaging applications, it is possible to harness the photoelectrically generated secondary particles. This is especially the case in microscopic and nanoscopic devices, for which attenuation of low-energy electrons is relatively small. In such devices, apart from photoelectrons, the role of Auger electrons is significant. Following photoabsorption, a cascade of Auger electrons may occur, which deposits energy at nanometer-micrometer distances, leading to measurable currents in those regions. Auger current has not been studied thus far for practical radiation detection. The energy deposition and formation of space charge from photoelectrons interacting with electrodes in semiconductor devices or wires have been recognized as a problem and studied to determine collection efficiency of electron hole pairs and thus far have not been utilized as a means of radiation detection. In semiconductors, the Auger effect could add to the space charge problem. In contrast, the Auger effect is a major contributor to signal formation

![Fig. 1. An example of a 7-layer HEC structure with high-Z copper and low-Z aluminum conductors and air as the dielectric. HEC induces LEC in the conductors, which is measured as detector signal.](image-url)
in the detector structures presented in this paper. Further, we are not aware of any reports on the use of photo-Auger current as the source of quantifiable signal in radiation detectors realized with alternating low-Z/high-Z layered microstructures or nanostructures, although photo-Auger-electron related signal enhancement has been investigated for thin-film high-Z structures.11

In this work, we experimentally and computationally investigate the radiation physics characteristics of prototype multi-layered HEC microstructures and demonstrate their feasibility for radiation detection and dosimetry in medical applications.

2. MATERIALS AND METHODS

2.A. Computer simulations

To demonstrate the principles of a HEC device, we assumed a planar geometry with two to seven thin electrically conducting high-Z and low-Z layers separated by dielectric layers. In particular, we considered high-Z (35 µm Cu, 100 µm Pb) and low-Z (250 µm Al) conducting layers separated by low-Z insulating layers (100 µm air gap), in the following order:

- AlCu, CuAl, AlPb, PbAl
- AlCuAl, AlPbAl
- AlCuAlCuAlCuAl, AlPbAlPbAlPbAl.

Ideally, the detector structures should be made of electrode materials such as gold and aluminum because gold has excellent radiation, mechanical, corrosion, and electrical properties, and we envision it as potentially the best material for a manufactured device. In the present experimental study, lead was used instead of gold because in this way, a large amount of inexpensive foils was readily available for testing and developing the fabrication skills necessary for repeatable experiments. Additionally, for the purpose of this study, the radiation transport properties of Pb in relation to those of Al and Cu are not substantially different from Au.

Each microstructure was enclosed between two 2-mm layers of water-equivalent material in order to simulate the experimental setup. A plane-parallel photon beam normally incident on the left-hand side of the detector, as shown in Fig. 1, was assumed. Simulation of radiation interactions with the microscopic structures was carried out for spectral sources (60, 80, 100, 120 kVp) using the cepxs/onedant deterministic radiation transport code.11 Further details of the simulations and the application of the cepxs/onedant code system for computing HEC are given by Zygmanski and Sajo.2,3 For the computer simulation, we obtained the incident x-ray spectra using the SpekCalc software for similar kVp and HVL parameters.13 Energy deposition, dose, and net current as function of spatial coordinate were computed and compared to experimental measurements. Net current is the arithmetic difference between the forward and the reverse leakage currents, with respect to the incident photon beam.2

2.B. Experiments

We fabricated dual- and multilayered microstructures with parameters given above. Various single detector elements (pixels) were tested in the present study. Detectors were made in various rectangular sizes (0.25–4 in. x 0.25–4 in.). In the case of multilayer structures, the active area ranged from 0.25 x 0.25 to 5 x 5 cm. A conventional radiotherapy simulator was used as the x-ray source (Ximatron, Varian Medical Systems), which produced a continuous exposure. The detectors were placed at the isocenter of a 25 cm field. Energy dependence was measured in the range of 60–120 kVp. Electric current was measured as a function of irradiation time using a commercial data acquisition system with 24 bits dynamic range, 0.4 fC sensitivity, and 0.9 ms sampling time (ADAS 128 channel current to digital converter, Analog Devices). In addition, doses, dose rates, and the actual output energy (kVp) of the simulator were independently measured for each nominal energy setting using an A12 ionization chamber and MagicMax™ photodiode (IBA) kVp dosimetry system. No external electric field, bias voltage, or signal amplification was applied.

3. RESULTS

Figure 2 shows an example of the computed net current2,3 as a function of distance from the front surface of the first conductor plate for two 7-layer detectors, AlCuAlCuAlCuAl

![Figure 2](image-url)

*Fig. 2. Computer simulation of net current j(x) as a function of distance from the front plate of the detector for different incident x-ray energies: 60 kVp, 80 kVp, 100 kVp, 120 kVp. The highest current between the conducting layers is for 60 kVp and the lowest for 120 kVp. X = 0 corresponds to the front surface of the detector structure where plane-parallel photons are normally incident. The entire structure was sandwiched between 2 mm water-equivalent material placed in the front and back. The unit of the computed leakage current is electrons per incident photon.*
and AlPbAlPbAlPbAl, exposed to four incident x-ray energies, 60, 80, 100, and 120 kVp. In these geometries, schematically shown in Fig. 1, three 35 µm Cu layers (or three 100 µm Pb layers) are sandwiched in four 250 µm Al layers. Air gaps between the conducting layers are 100 µm, each. The dashed vertical lines show the center of the air gaps. Negative net current implies that more high-energy electrons are moving in the reverse (opposite to the direction of the primary photon beam) than in the forward direction. The units of particle current are electrons per incident x-ray photon while the experimental signal is expressed in nA. Of these two cases, the detector with Pb layers shows significantly larger currents in the first layer but it also exhibits a progressive decrease with distance due to attenuation of x-rays in the lead layers.

The experiments were conducted using the same geometry as those used in the computations. Figure 3 shows a comparison of the average computed HEC, moving from the high-Z conductors (Cu and Pb) toward the Al anode, versus the experimental signal, in nA/cm², for unit air kerma (1 Gy/s) for the 7-layer detectors, AlCuAlCuAlCuAl and AlPbAlPbAlPbAl. Signal for each high-Z conductor layer was measured separately (Cu₁, Cu₂, Cu₃ and Pb₁, Pb₂, Pb₃) and combined from all three layers (Cu₁+₂+₃ and Pb₁+₂+₃). As it is seen, even though the current for Pb₃ is greater than that for Cu₁, the overall efficiency of the multilayer AlPbAlPbAlPbAl detector is not greater than that of the AlCuAlCuAlCuAl layers, as the signals Cu₁+₂+₃ ≈ Pb₁+₂+₃. This is because the much greater thickness of the Pb layers and their larger photoelectric cross section result in greater photon and electron absorption and electron energy loss inside the 100 µm Pb layers compared to the 35 µm Cu layers. Therefore, thin layers of high-Z materials, not much thicker than the mean secondary electron range therein, are more efficient in generating HEC. In all cases presented in this paper, the external voltage across electrodes was zero. The internal voltage due to contact potential was experimentally determined to be on the order of 0.2 V (Al–Pb), 0.6 V (Cu–Pb), 0.7 V (Al–Cu). The errors in Fig. 3 comprise of systematic errors in fabrication, experimental setup, and noise and were obtained by multiple irradiations of similar samples.

Figure 4 shows the energy (kVp) dependence of experimental vs simulated currents in two 3-layer detectors, normalized to dose in water for equivalent irradiation conditions and geometry. Normalization of HEC currents was done to take away the dependence of the experimental data on the x-ray tube output, which permits comparison to simulated data. The small difference between the two cases AlCuAl and AlPbAl is due to the different K- and L-shell energies of Cu and Pb, their photoelectric cross sections, and fluorescent and Auger yields. Differences in Cu and Pb conductivities also play a role in the experimental measurements. Figure 5 shows the corresponding ratios of National Institute of Standards and Technology (NIST) mass energy absorption coefficients for copper and lead to that of water as a function of keV (A) and kV (B). When the mass energy coefficients are convolved over the whole spectral range, their ratios are relatively independent of kVp potential. This partially explains the low variability of normalized HEC signals in Fig. 4. Although the pointwise ratios of the mass energy absorption coefficients exhibit a significant variation over energy [Fig. 5(A)], when they are convolved with the incident photon spectra (which represents a nonuniform probability density), their ratio becomes relatively insensitive to the kVp potential [Fig. 5(B)]. This partially explains the low variability of the normalized HEC signals in Fig. 4. In addition, there are other effects related to electrodynamics that give rise to material dependent responses at the high-Z/low-Z interfaces.

Integrated (cumulative) signal (charge) as a function of dose (exposure time) is linear for fluoroscopic x-ray tube currents (1–4 mA) as seen in Fig. 6(A). Note, all our measurements were taken as a function of time with about 1 ms sampling time. Exposures used in this study depended on the mA and total ms setting used. For example, some of them were taken for 0.759, 1.351, 2.062, 2.860 R equivalent to 6.7, 11.9, 18.1, 25.1 mGy for 60, 80, 100, 120 kVp. A photograph of one of the prototype HEC detectors is seen in Fig. 6(B). The detector has been disassembled to show the details inside.
4. DISCUSSION

Conventional detectors in medical imaging and related applications invariably aim to achieve high photon interaction rate in order to improve the detection efficiency. This requires increased detector material density and/or thickness. In addition, high conversion efficiency so as to maximize the production of secondary charge carriers is an important goal, as is the application of external electric field for the efficient collection of these charges. The signal usually must be amplified to permit subsequent processing.

The HEC detector concept is fundamentally different from the aforementioned paradigm. Here, reducing the thickness of the detector increases the intrinsic conversion efficiency, which we define as the generation of measurable signal per unit absorbed dose. Whereas in conventional detectors, the interaction rate and the material quantum efficiency are maximized, in the HEC detector, the objective is to maximize the collectable charges per interaction. This means that the beam absorption is a minor fraction of that normally seen or desired in conventional detectors. For example, in our prototype devices, the approximate absorption per layer was as low as ~3%. Using optimized high-Z material thickness, this figure is likely reduced to below 1%. Although the interaction rate of the incident beam is low because of the small thickness, those photons that interact have a high average yield of secondary electrons. Therefore, the intrinsic efficiency (per absorbed x-ray) is much higher than what is currently achieved using thick bulk active layer designs. An important result of this is that the HEC device does not require sophisticated on the chip electronics in its basic form; it does not need external bias voltage to collect the charges and no signal amplification is necessary. In concert, this gives rise to a device, which is very simple and the cost of its fabrication is extremely low, with components commonly available. Further, it would be very reliable and rugged, not susceptible to environmental factors, including radiation damage or aging.

As a monitoring device or dosimeter, the HEC detector can be very thin and composed of only two low-Z/high-Z layers, similarly to standard point dose detectors, such as ion chambers or diodes, which detect a very small fraction of incident photons. For applications, in which more x-rays must be stopped, the HEC detector can be made thicker by increasing the number of the thin layers and virtually stopping all the keV-range x-rays while utilizing them with high efficiency. In addition or instead of increasing the number of layers, the detector area can be also made larger to strengthen the signal. The latter may be an acceptable strategy in some applications, but not in imaging for which high spatial resolution is required and which has not been tested in the present study.

HEC can be utilized as the primary means of charge carrier transport in any low-density dielectric provided that the separation between the cathode and anode is not larger than the range of HEC electrons. The same concept applies to the high-Z cathode, which has to be sufficiently thin to allow the electrons to escape. Any thicker cathode would increase the beam attenuation without further contribution to HEC electrons available to form the signal. Thus, the best efficiency is likely to
be observed in nanostructures or microstructures, or in meta-
materials with periodic nanostructures with cavities or voids. 
Increased number of layers or increased thickness of the layers 
or their Z value results in greater overall absorption of the 
primary radiation. The latter also has a degrading effect of self-
attenuation, impacting low-energy Auger and photoelectrons. 
The combined effect is illustrated in Fig. 3 where 100 µm thick 
Pb layers clearly reduce the efficiency of HEC conversion, as 
Pb₂ < Pb₁ < Pb₀ by nearly a factor of 2 in each step.

The magnitude of the signals for the detectors examined 
in this work varied depending on the number of layers, 
material type, and incident photon energy, and it was about 
30–150 nA/cm² for unit air kerma (1 Gy). Furthermore, the 
response of detectors having different area and shape was 
proportional to the total overlap area between the conductive 
layers. All experimental data were acquired as a function of 
time with about 1 ms sampling time. The lowest fluoroscopic 
beam of 1 mA available on the x-ray equipment resulted 
in measured HEC currents on the order of 0.1–0.2 nA (for 
different type of detectors). Based on these results, we infer 
that for 100 ms sampling time, it would be possible to measure 
the time dependence of x-ray beams with ten times lower x-ray 
tube current (e.g., 0.1 mA) with confidence. These currents 
correspond to about 40 nGy for each 100 ms detector point. 
For longer data acquisition times (e.g., 1 s) even lower dose 
rates could be reliably measured because of longer integration 
time.

Within the examined range of 60–120 kVp, the energy 
dependence of the HEC normalized to the x-ray tube output 
is relatively small. In the case when Cu cathode is used in 
the HEC detector, nearly all interactions occur with the K-
shell (∼9 keV). But for Pb cathode, x-ray energies below 
its K-edge (88 keV) will interact with mostly the L-shells 
(13–15.9 keV), while increasing the x-ray energy above 
88 keV gradually makes more photons available that can also 
interact with its K-shell. In Cu, as the incident x-ray beam 
energy is increased, the photoelectric cross section gradually 
decreases. Therefore, a commensurate decrease in j(x) should 
be seen. However, photoelectrons produced in this way will 
possess higher energies. This will have an effect of increasing 
the j(x) because these higher energy electrons can further 
ionize and contribute to the leakage current. These are two 
competing processes from the perspective of j(x). But because 
the photoelectric cross section drops with the ∼3rd power 
of energy, the decrease in j(x) will dominate. This can be seen in 
the tendency of both experimental and computational results 
in Fig. 4. In the case of Pb cathode, below x-ray energies 
of about 88 keV, almost all interactions will be with L- 
and M-shell electrons. As the incident beam energy is increased, 
there will be fewer M- and L-shell electron production but 
there will be more K-shell ionizations, yielding relatively low-
energy electrons liberated from the K-shell. These will replace 
the gradually diminishing number of L and M electrons. 
Therefore, the HEC stays relatively constant above ∼80 keV 
x-ray energies. However, for continuous kVp spectra, these 
effects are washed out, which may also be inferred from the 
kVp dependence of the ratio of NIST mass energy absorption 
coefficients of lead (copper) to water (Fig. 5).

Systematic determination of sensitivity, reproducibility, 
and performance of HEC prototypes to commercial detectors 
for specific applications was not pursued in the present study. 
Sensitivity of down to about 20–50 nGy was estimated based 
on a series of measurements as a function of mA (1–200 mA) 
by extrapolation to smaller values. Signal to noise ratio (SNR) 
deeds on mAs, material, and geometry of the detector, and 
on the sampling time. For 900 µs sampling time, SNR 
in time domain varied from about 50 (1 mAs) to 1000 
(200 mAs). Larger SNR is expected for larger sampling times. 
Reproducibility was within a 1%–5% depending on the fabrica-
tion quality. Performance of HEC prototypes normalized to 
MagicMax (IBA) dose for x-ray tube output 40–120 kVp, is 
displayed in Fig. 4. Note, the total experimental signal has two 
contributions: direct high-energy current and HEC induced 
ionization of the dielectric (air) and creation of charge carriers 
(ions), which are transported across the contact potential. In 
the simulation of radiation transport in Fig. 2, transport of 
charge carriers in electric field is not simulated and thus 
it only accounts for the first contribution. The exact x-ray 
flux was not known, and dose or air kerma in air was used 
instead. Air kerma was measured using standard kV dosimeter 
(MagicMax). In addition, note the number of x-rays stopped 
in MagicMax is greater than in the HEC detectors.

At the present, the early prototypes of HEC detector 
is not intended to be used as a high-resolution imaging 
device; pixilation at the submillimeter scale has not been 
attempted. We expect that resolutions of about 1 mm can 
be straightforwardly obtained for 1D arrays as shown in 
a parallel study. For x-ray beam monitoring applications, 
large square or rectangular pixels are feasible (a few 
millimeters to a few centimeters, for example), which may 
be sufficient for 2D dosimetry in interventional radiology 
applications (e.g., fluoroscopy) as proposed by Goertz. 
However, fabrication of 2D arrays requires industrial methods. 
Fortunately, with established thin-film industrial techniques, 
fabrication of very small pixels would be relatively easy 
compared to other detectors (amorphous silicon, for example), 
because conductors such as copper can be easily deposited in 
just about any pattern on a substrate and unlike a–Si or CCDs, 
the structure of the HEC detector is very simple.

Compared to photodiodes operating in the photovoltaic 
mode, which also do not require bias voltage or require 
only a small bias when operated in the photoconductive 
mode, the HEC detector has several advantages. Based 
on our experience with the prototype HEC detectors, it is 
relatively simple and inexpensive to manufacture and to 
optimize it for specific purposes. In principle, it can be made 
flexible and cut to any size and shape. In a single sandwiched 
configuration, it is largely transparent to radiation; thus, it does 
not generate artifacts in transmission dosimetry. Most thin-
film photodiodes are not made to detect x-rays directly and 
those that are made specifically for this purpose are inherently 
much more expensive than the HEC detector.

Our results encourage further development in this area. It 
is likely that various medical applications will benefit from 
single or multiple HEC detectors or from HEC detector arrays. 
Specific applications require additional research.
5. CONCLUSIONS

We have shown both experimentally and computationally that secondary high-energy electrons moving through periodic high-$Z$/low-$Z$ multilayer structures can be effectively harnessed for detection of ionizing radiation, as predicted by Zygmanski and Sajo. The proposed detection mechanism is a direct conversion of energy of the ionizing radiation to usable signal via induction of low energy currents in the conductors which do not require external power supply or amplification. This is a promising mechanism that can become enabling technology for new selfpowered or low power radiation detectors or devices in real-time and in vivo.

ACKNOWLEDGMENTS

This work was supported in part by contract FA8051-15-P-0010 from the Air Force Civil Engineer Center–East, Tyndall AFB, FL.

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