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Semiconductor scintillator based on photon recycling

Serge Luryi*, Arsen V. Subashiev

University at Stony Brook, ECE Department and NY State Center for Advanced Sensor Technology, Stony Brook, NY 11794-2350, USA

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ABSTRACT

Direct-bandgap semiconductor with high quantum radiative efficiency can operate as a scintillator despite being "opaque" to its own luminescence. An interband absorption does not finish off the luminescence but merely creates a new minority carrier, which in turn recombines in a predominately radiative fashion. To take full advantage of this "photon recycling" effect, optically-tight integration of photoreceivers on both sides of the semiconductor scintillator wafer is desirable.

1. Introduction

The key issue in implementing a semiconductor scintillator is to make sure that photons generated deep inside the semiconductor slab could reach its surface without tangible attenuation. However, semiconductors are usually opaque at wavelengths corresponding to their radiative emission spectrum. Our group has been working on the implementation of scintillators based on direct-gap semiconductors, like InP or GaAs. For the exemplary case of InP the luminescence spectrum is a band of wavelengths near 920 nm.

The original idea [1] was to make InP relatively transparent to this radiation by doping it heavily with donor impurities, so as to introduce the Burstein shift between the emission and the absorption spectra. The problem with this approach is attenuation of the optical signal by the free-carrier absorption (FCA) in heavily-doped material.

Here we shall describe another approach, based on the extremely high quantum radiative efficiency of high-quality direct-gap semiconductors, such as InP. In these materials, an act of interband absorption does not finish off the luminescent photon; it merely creates a new minority carrier and then a new photon in a random direction. This phenomenon, known as photon recycling [2,3], has been used [4] to explain long radiative lifetimes in GaAs/AlGaAs heterostructures.

In doped semiconductors, the incident radiation induces *minority* carriers, while the concentration of majority carriers does not measurably change. Every reaction on the way to luminescence, including Auger recombination, is *linear* with respect to the concentration of minority carriers. One can therefore expect that semiconductor scintillators will not exhibit effects of non-proportionality and their ultimate energy resolution could be on par with that of diode detectors implemented in the same material.

The proportionality of scintillation yield is not the only expected advantage of semiconductor scintillators. One of the major benefits of semiconductor materials is the mature technology that enables the implementation of epitaxial photodiodes integrated on the surface of a semiconductor slab [5]. The epitaxial diode provides nearly perfect registration efficiency of photons that have reached the heterointerface.

A semiconductor scintillator endowed with an integrated photoreceiver can be patterned into a two-dimensional array of pixels. Such an array forms a basic unit that can be stacked up indefinitely in the third direction. This enables three-dimensional integration of scintillator "voxels" and thus offers a tantalizing possibility of implementing a compact low-voltage Compton telescope [6].

2. Photon recycling

Consider an InP scintillator slab with two photoreceiver systems integrated on the opposite sides of the slab [7]. Let the interaction of strength G occur a distance z from the detector top surface, as indicated in Fig. 1. The minority carrier ("hole" h) has the probability η (radiative efficiency) to generate a photon (of energy spectrum S). The generated photon can either reach the detectors (probabilities p_1 and p_2, respectively) or disappear through FCA (probability p_{fca}). All these probabilities depend on position z. The combined probability $P(z)=p_1+p_2+p_{fca}$ describes the likelihood of the photon loss at this stage and the alternative, $1-P(z)$, is the probability that a new hole is created. The cycle of hole–photon–hole transformation repeats *ad infinitum*, as illustrated in the diagram in Fig. 1. Most of the scintillations reaching the detectors' surface are not photons directly generated at the site of the gamma particle interaction, but photons that have been re-absorbed and re-emitted a multiple number of times.

* Corresponding author.
E-mail address: Serge.Luryi@StonyBrook.edu (S. Luryi).

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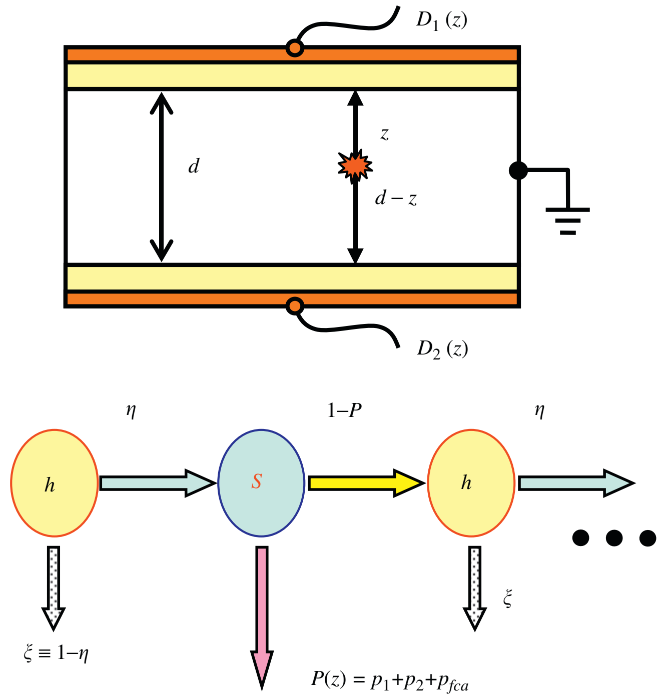

Fig. 1. Schematic cross-section and a diagram of the basic radiative processes in an InP scintillator with two epitaxial InGaAsP photodiodes grown on both sides. The radiative efficiency is defined in terms of the radiative (ν_r) and nonradiative (ν_{nr}) transition rates, $\eta = \nu_r/(\nu_r+\nu_{nr})$.

Let the luminescent signal comprise the energy spectrum $S(E)=GS_0(E)$ (where S_0 is normalized to unity, $\int S_0(E)dE=1$). The emitted energy is isotropic, so that the energy emitted in unit energy interval per unit solid angle is $(G/4\pi)S_0(E)$. The energy $D_i(z)$ reaching the ith detector surface ($i=1, 2$) is attenuated in a way that depends on z.

In the presence of absorption, characterized by the interband absorption coefficient $\alpha_i(E)$, the detection probability for a photon at energy E (averaged over all angles) is given by

$$\pi(E,z) = \int_0^\infty \exp[-\alpha_i(E)r]\frac{\cos\theta}{2r^2}\rho d\rho \quad (1)$$

where $\rho = z\tan\theta$ and $r = z/\cos\theta$. Averaged over the emitted photon spectrum $S(E)$, the probability p_1 that an emitted photon reaches the 1st photodiode at $z=0$ is given by

$$p_1(z) = \int \pi(E,z)S(E)dE \quad (2)$$

The probability (2) and the similar quantity for the 2nd photodiode, $p_2(z)=p_1(d-z)$, are referred to as *single-pass* probabilities, because they do not include the subsequent fate (recycling) of the absorbed photon.

The single-pass probability p_{fca} of free-carrier absorption can be estimated in a similar fashion, in terms of the FCA absorption coefficient $\alpha_e(E)$, viz.

$$p_{fca} = \int \frac{\alpha_e}{\alpha_e+\alpha_i}S(E)\left[1-\pi(E,z)-\pi(E,d-z)\right]dE \quad (3)$$

So long as the photon recycling process continues, the minority carriers (holes) and photons are interchangeable entities. The process can be finished off by FCA while the entity is photon or, while the entity is hole, by nonradiative transitions that occur with the small probability $\xi = 1-\eta$ (in our samples η ranges from 90 to 99%).

The detector signals D_1 and D_2 add single-pass contributions from different cycles. As is evident from Fig. 1, the sum can be found as geometric progression, giving

$$D_i(z) = G\eta p_i(z) \times \sum_{n=0}[\eta(1-P)]^n = \frac{G\eta p_i(z)}{\xi+\eta P(z)} \quad i=1,2 \quad (4)$$

and the total photon collection efficiency, $\mathrm{PCE} \equiv (D_1+D_2)/G$, is given by

$$\mathrm{PCE} = \frac{p_1(z)+p_2(z)}{[(\nu_{nr}/\nu_r)+p_{fca}(z)]+[p_1(z)+p_2(z)]} \quad (5)$$

We note that for high photon recycling ($\eta \to 1$ and $p_{fca} \to 0$) one has an ideal scintillator in the sense that the entire generated luminescence is collected – even though the single-pass probabilities p_1 and p_2 may not be high due to interband absorption.

Fig. 2 shows the photon collection efficiency for InP scintillator doped n-type with the concentration $N_D = 3\times10^{17}\,\mathrm{cm}^{-3}$. The calculation is based on Eqs. (4) and (5) and measured quantum efficiency η (Fig. 3a) and the FCA absorption coefficient α_e (Fig. 3b).

The only approximation involved in Eq. (4) is the assumption that every act of recycling occurs at the same place z where the initial interaction occurred, and therefore the same probabilities $p_1(z)$ and $p_2(z)$ appear at all stages of the recycling, see Fig. 1. This has reduced the summation of an infinite series to a geometric progression and allowed us to obtain the result in a closed form. In reality, however, there is photon-assisted transport of holes in photon recycling, which has the nature of a random walk [6]. We have evaluated this effect (to be published separately) and found that its inclusion does not change the results qualitatively, although it does slightly enhance the estimate of PCE.

As seen from Fig. 2a, photon recycling delivers a reasonable fraction of the scintillating photons to the wafer surface. However, this fraction depends on the exact position of the interaction

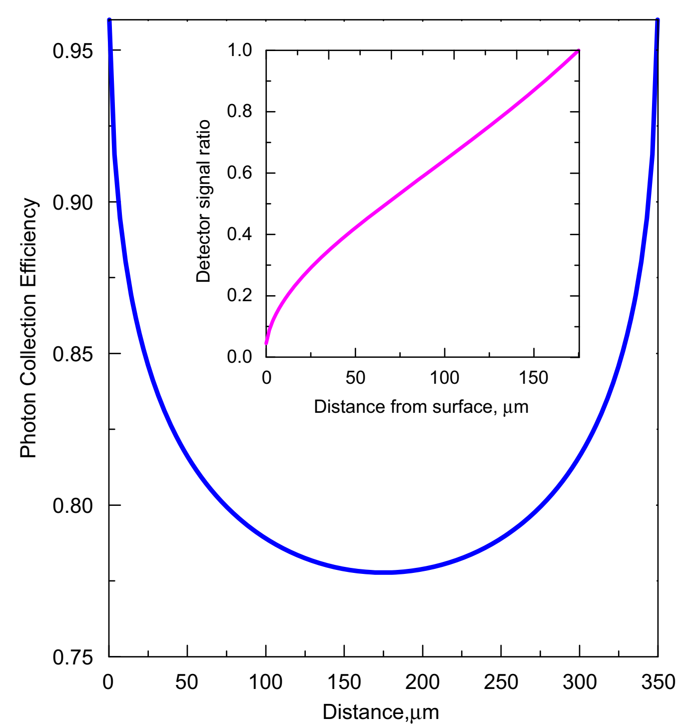

Fig. 2. Room temperature photon collection efficiency in an InP scintillator of thickness $d=350\,\mu$m, doped to $N_D = 3\times10^{17}\,\mathrm{cm}^{-3}$, as a function of the event distance z from the surface. The inset shows the ratio of detector signals $\rho = D_1/D_2$. The ratio is shown for $z \le d/2$, since by symmetry, one has $\rho(z) = \rho^{-1}(d-z)$.

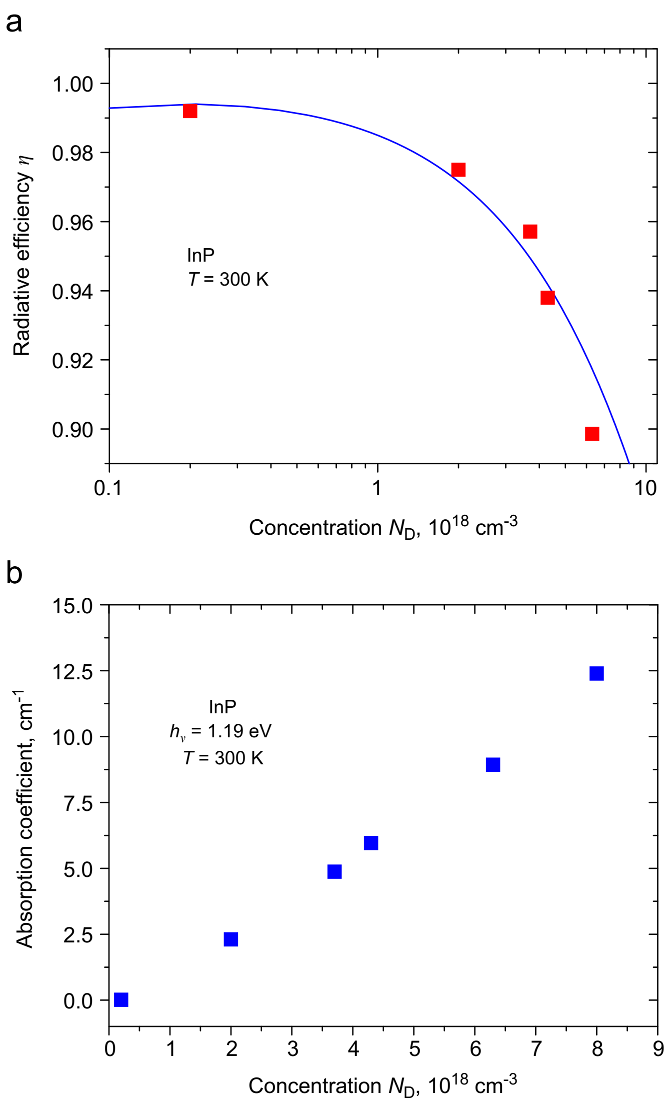

Fig. 3. Dopant concentration dependences of the radiative efficiency (a) and the FCA absorption coefficient (b).

site relative to the surface. The problem is how to distinguish the signal arising from a large energy deposited far from the photoreceiver surface from that arising from smaller energy deposited nearby. The problem arises from the attenuation of the optical signal. However, if we knew the distance z of the gamma interaction event from the photoreceiver surface, we could correct for the attenuation.

The solution is based on tallying the signals D_1 and D_2 individually. The inset to Fig. 2 shows that the ratio of detector signals $\rho \equiv D_1/D_2 = p_1/p_2$ is an excellent measure of z. The simultaneous detection by *both* detectors of the scintillation arising from the same interaction event, allows us to determine the position of the interaction and therefore correct for attenuation.

3. Conclusion

The efficiency of photon collection in direct-gap semiconductors is limited by parasitic processes, such as FCA and nonradiative recombination of the minority carriers. If these are minimized, one can have an opaque but "ideal" (in terms of the photon collection efficiency) semiconductor scintillator. A nearly ideal scintillator is provided by a lightly-doped InP wafer endowed on both sides with integrated photoreceivers.

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