

# Semiconductor Scintillator and 3D Integration

Serge Luryi

Department of Electrical and Computer Engineering  
State University of New York at Stony Brook  
Stony Brook, NY, USA 11794-2350

**Abstract**—We discuss the feasibility of novel gamma radiation detectors with excellent isotope discrimination and angular resolution of the direction to source. The new detector combines specially designed semiconductor heterostructures in a monolithic 3D integrated device that has important applications in the prevention of terrorist threat.

*Semiconductor heterostructures,  $\gamma$ -detectors, scintillators, 3D pixellation, isotope discrimination, angular determination*

## I. INTRODUCTION

There are two large groups of solid-state radiation detectors, which dominate the area of ionizing radiation measurements, scintillation detectors and semiconductor diodes. The scintillators detect high-energy radiation through generation of light which is subsequently registered by a photo-detector that converts light into an electrical signal. As reviewed extensively by Knoll, both groups of detectors have their drawbacks, resulting in a lower than desired signal response and resolution as well as lower speed of response. It appears very attractive to employ direct-gap semiconductors as scintillators, operating at interband recombination wavelengths, with nearly 100% conversion efficiency and exceptionally fast response. The key issue is how to make the semiconductor essentially transparent to its own infrared light, so that photons generated deep inside the semiconductor slab could reach its surface without tangible attenuation. We propose two novel ways to accomplish this, one based on doping a uniform semiconductor with shallow donors to produce the Burstein shift between emission and absorption spectra, the other on the growth of thick bandgap-engineered heterostructures.

## II. PHYSICAL PRINCIPLES

### A. Scintillator based on Burstein shift

When semiconductor is heavily doped, the edge of absorption is blue-shifted relative to the emission edge by the carrier Fermi energy. This quantum effect, called the Burstein shift, underlies operation of all semiconductor lasers. For band edge photons (Fig. 1) the absorption length  $\lambda = \lambda_0 \exp(E_F/kT)$  increases exponentially with the Fermi level  $E_F$ , compared to its value in the undoped material ( $\lambda_0 \approx 1\mu\text{m}$  in InP). Besides making the semiconductor transparent to its own emitted photons, the heavy doping shortens the radiative recombination time  $\tau$  of minority carriers, according to  $\tau = 1/BN_D$ , where  $B=10^{-10}\text{ cm}^3/\text{s}$  is the radiative recombination coefficient. For the donor concentration  $N_D = 10^{19}\text{ cm}^{-3}$  in InP, one has  $\tau \sim 10^{-9}\text{ s}$ . The non-radiative time in this range of

concentrations is limited by Auger recombination and is of order  $\sim 10^{-7}\text{ s}$ . Therefore, the ratio  $\xi$  of the radiative recombination time to the non-radiative time is about  $\xi \sim 0.01$ . Thus, the device experiences practically no losses through the non-radiative channels of recombination. For  $N_D = 10^{19}\text{ cm}^{-3}$ , the ratio  $E_F/kT \sim 8$  in InP at room temperature, thus yielding the absorption length  $\lambda \approx 3\text{ mm}$ . Further increase of the doping, desirable for the increase of the  $E_F/kT$  ratio, becomes impractical due to the rise of the *free-carrier absorption*, limiting  $\lambda$  to  $\approx 1\text{ mm}$  at room temperature, which is still larger than the standard thickness of an InP wafer. This optimistic estimate does not include smearing of the absorption edge by fluctuations in carrier concentration.

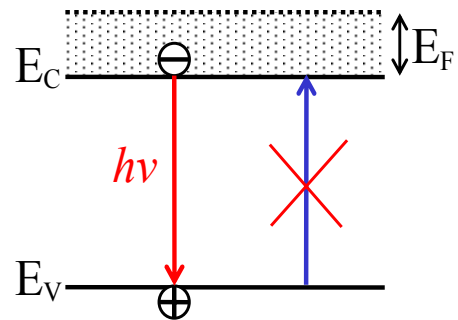


Figure 1. Illustration of the Burstein shift between the emission and the absorption spectra in heavily doped semiconductors. Absorption of photons  $h\nu$ , emitted by recombining electrons and holes, is suppressed by the absence of vacant states in the conduction band under the Fermi level.

### B. Heterostructure scintillator

The uniform scintillator, based on the Burstein shift, is limited by the combination of interband and free-carrier absorption to a thickness of about 1 mm at room temperature. Let us now discuss a modified structure, where the problem of absorption is largely eliminated, Fig. 2. The epitaxial structure comprises two alternating materials lattice-matched to each other. The materials are assumed to have different energy gaps, with the second material having the lower bandgap. We further assume the second material is doped, while the first material is largely undoped. For illustration purposes, we shall consider InP based heterostructure.

The essential idea is that the total volume occupied by the second material is small compared to that occupied by the first material. For example, if a  $2\mu\text{m}$ -thick InP layers are alternated by a 20 nm-thick layers of InGaAsP, the layer thickness ratio is 100 (duty cycle factor  $\delta=0.01$ ). Upon interaction with the

ionizing radiation, the created electrons and holes quickly, within about a nanosecond, diffuse to the wells and recombine there. The difference in the band-gap energies guarantees that all light emission occurs in the InGaAs wells, so that the wider-gap InP remains substantially transparent to the emitted photons. The only remaining absorption in the heterostructure is owing to self-absorption in the wells. This effect of interband self-absorption is further suppressed by increasing the carrier density in the wells, effecting the Burstein shift.

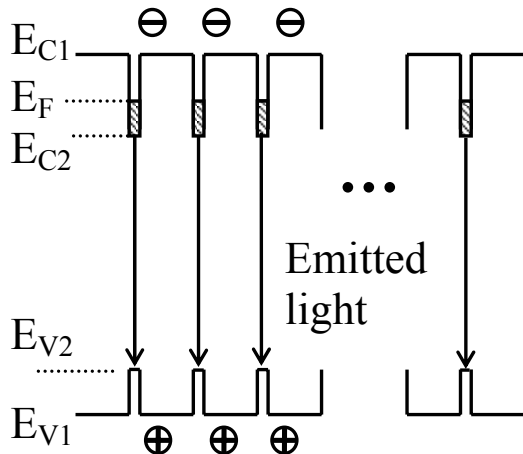


Figure 2. Heterostructure scintillator based on bandgap engineering. Electrons and holes generated by the ionizing radiation rapidly diffuse to the narrow-gap wells and recombine there, producing scintillating radiation to which the heterostructure material is largely transparent.

### III. GENERAL ADVANTAGES OF THE DIRECT-GAP SEMICONDUCTOR SCINTILLATOR; 3D INTEGRATION

The direct-gap scintillator has high detection efficiency and a response time in the nanosecond range. We note that this prompt response is due to the short radiative lifetime of minority carriers and is *not* owing to the quenching of the radiative transitions by non-radiative processes. Therefore, it is not accompanied by any degradation of brightness. Regarding the efficiency, it is instructive to compare our device with a successful classical scintillator, the thallium-activated sodium iodide. In the NaI scintillators electron-hole pairs are produced across the band-gap of over 7 eV (the characteristic ionization energy per e-h pair  $E_i \sim 3E_G \approx 25$  eV) while the scintillating photons are produced at  $h\nu$  of only 3 eV, whence the best available efficiency is about 12%. In contrast, the  $h\nu$  of scintillating photons in direct-gap semiconductors is close to  $E_G$ , while  $E_i \approx 4.1$  eV in both InP and GaAs, This improves the efficiency by at least a factor of 7/3.

However, the most innovative feature of the proposed detector is that it enables 3D integration of standard semiconductor wafers, each provided with a pixellated epitaxial photosensitive layer on its surface as well as amplifying and analog-to-digital electronic circuits. Such systems can then be stacked up without limit, as illustrated in Fig. 3, thus increasing the active detector volume to accommodate virtually any absorption length of high-energy

radiation – without any loss in the scintillator yield or speed of response. The information about each ionizing radiation event, comprising simultaneous response from several three-dimensional (3D) pixels, is converted to digital form, suitable for rapid analysis. The 3D pixellation of the scintillator response enables *both* accurate determination of incident particle energy *and* high-resolution angular discrimination.

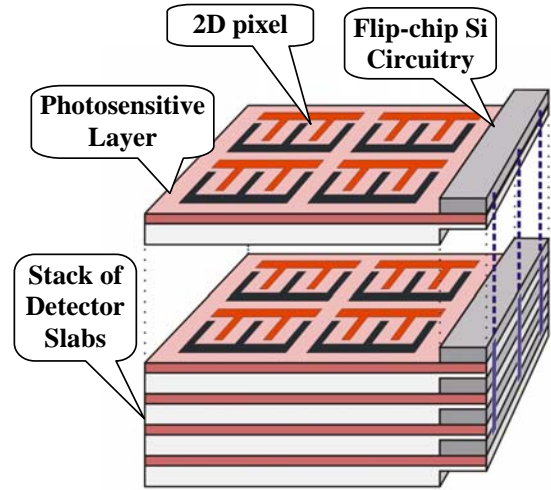


Figure 3. Three-dimensionally pixellated scintillator system

Breaking down the ionizing interaction into events, resolved both in space and in energy, is well known to offer dramatically higher information content, compared to measuring only the total energy deposited by the ionizing particle. A large body of research exists to use this enhanced information in the so-called Compton telescopes [3]. Compared to the existing Compton telescopes, built as an assembly of discrete detectors (usually Ge diodes), the compact monolithic 3D–pixellated device we propose has multiple advantages that are reminiscent of those brought to electronics by the advent of integrated circuits.

Preliminary estimates suggest that for 660 keV  $\gamma$ -photons we should be able to determine the energy with accuracy in the range of 1 to 3 keV, corresponding to an energy resolution better than 0.5%. This means that our 3D-integrated scintillator will have the isotope discrimination power similar to that of the best semiconductor diodes. At the same time, it should be able to resolve accurately (to better than  $1^\circ$ ) the direction to a point source. Both of these features are of great importance for anti-terrorist security applications.

### REFERENCES

- [1] G.F. Knoll, *Radiation Detection and Measurement*, 3<sup>rd</sup> edition, John Wiley & Sons, Inc. (2000).
- [2] A. Kastalsky, S. Luryi, and B. Spivak, “Semiconductor high-energy radiation scintillation detector”, *Nucl. Instr. and Meth. in Phys. Res. A* **565**, pp. 650-656 (2006).
- [3] S.E. Boggs and P. Jean, “Event reconstruction in high resolution Compton telescopes”, *Astron. Astrophys. Suppl. Ser.* **145**, pp. 311-321 (2000).