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Semiconductor high-energy radiation scintillation detector

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Abstract

We propose a new scintillation-type detector in which high-energy radiation generates electron–hole pairs in a direct-gap semiconductor material that subsequently recombine producing infrared light to be registered by a photo-detector. The key issue is how to make the semiconductor essentially transparent to its own infrared light, so that photons generated deep inside the semiconductor could reach its surface without tangible attenuation. We discuss two ways to accomplish this, one based on doping the semiconductor with shallow impurities of one polarity type, preferably donors, the other by heterostructure bandgap engineering. The proposed semiconductor scintillator combines the best properties of currently existing radiation detectors and can be used for both simple radiation monitoring, like a Geiger counter, and for high-resolution spectrography of the high-energy radiation. An important advantage of the proposed detector is its fast response time, about 1 ns, essentially limited only by the recombination time of minority carriers. Notably, the fast response comes without any degradation in brightness. When the scintillator is implemented in a qualified semiconductor material (such as InP or GaAs), the photo-detector and associated circuits can be epitaxially integrated on the scintillator slab and the structure can be stacked-up to achieve virtually any desired absorption capability.

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1. 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, typically a photo-multiplier that converts light into an electrical signal. The main advantage of existing scintillators is their large detection volume. Semiconductor diodes employ reverse biased p–n junctions or metal–semiconductor junctions where the absorbed radiation creates electrons and holes, which are separated by the junction field thereby producing a direct electrical response. The sensitivity of diode detectors depends on the length of the field region. To increase this length, the doping level in the field region must be minimized. At present, the semiconductor diode is best for the spectral resolution of the ionizing radiation.

As reviewed extensively by Knoll [1], both groups of detectors have their drawbacks, resulting in a lower than desired signal response and resolution. The diodes typically suffer from inadequate electron–hole collection, i.e., not every electron–hole pair created by the radiation results in a current flow in the measurement circuit. The most common semiconductor materials used for the radiation detectors are Si and Ge p–n junctions, where the intrinsic carrier concentration can be reduced to a very low level, while the excellent material properties provide for good electric field uniformity. In the case of silicon, an additional procedure of Li doping is commonly applied to neutralize acceptors in the depletion region, in order to obtain an acceptable junction depletion length. The Si:Li detectors, however, need low temperatures, both during the operation and in storage. Both Si and Ge radiation detectors require

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relatively high voltages, typically of order kilovolts, to maximize the collection of electrons and holes and increase their drift velocity. This results in an additional unwelcome noise in the current response and leads to problems of surface conductance and voltage breakdown. Even at these high voltages, the response time is larger than 100 ns, limited by the saturated electron and hole drift velocities at high fields. Finally, the dependence of the shape of the output pulse rise on the position at which the electron–hole pairs are created, significantly complicate the measurements.

In the case of scintillators, the efficiency of converting the high-energy radiation into light is typically about 10% (12% in NaI). The reason for this is fundamental: the scintillator material must be transparent to the radiation it produces. To accomplish this, the wide-gap material (7 eV for NaI) is activated with impurities such as thallium which represent recombination sites for electrons and holes. Thus produced light has much lower energy (3 eV for Tl) than the bandgap of the host crystal, whence the poor efficiency. In addition, the recombination time on such impurities is several hundreds of nanoseconds (e.g., 230 ns for NaI activated with Tl), which is undesirably long for fast timing or high counting rate applications. Finally, the high bandgap inherent in all commercially available scintillators implies a relatively high energy (25 eV for NaI) required per each electron–hole pair created by the ionizing radiation. This reduces the detector resolution.

A group at the Lawrence Berkeley National Laboratory has been working on a semiconductor scintillator wherein a direct-gap semiconductor like CdS or ZnO is doped with donors in a reducing atmosphere to provide electrons in shallow states below the conduction band [2], and with radiative centers to trap ionization holes [3,4]. If the radiative centers are ionized acceptors, self-absorption can be reduced by limiting their concentration. If the radiative centers are isoelectronic atoms, holes are trapped in local states, and the subsequent lattice relaxation results in a Stokes shift that further reduces self-absorption. The success of these approaches depends on the elimination of non-radiative centers that limit luminosity [5].

We propose a new scintillation-type semiconductor detector in which high-energy radiation produces electron–hole pairs in a direct-gap semiconductor material that subsequently undergo *interband recombination,* producing infrared light to be registered by a photo-detector. 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 contemplate two ways to accomplish this. One (relatively inexpensive) way, based on heavy doping of bulk semiconductor with shallow impurities of one polarity type, preferably donors, is discussed in Section 2. The allowable slab thickness depends on temperature and is ultimately limited by free-carrier absorption to about 1 mm (Section 3). This limitation is essentially lifted in our other approach, discussed in Sections 4 and 5, which requires an epitaxially grown thick heterostructure of variable bandgap. This approach is, naturally, more expensive to produce, but the additional slab thickness it offers, especially in room-temperature operation, should justify the effort. Both devices are contemplated for the implementation in compound semiconductor materials, such as GaAs or InP, where a mature optoelectronic technology exists. This enables a novel system architecture, discussed in Section 6, where each relatively thin (say, 1 mm thick) semiconductor slab is supplied with its own, epitaxially grown or grafted on the surface, photo-detector system. Such systems can then be stacked up without limit, thus increasing the active detector volume to accommodate large absorption length of high-energy radiation.

2. Scintillator based on Burstein shift in bulk semiconductor

The key requirement for a scintillator is to be transparent to its own radiation, so that the photons produced deep inside the material can reach the surface and be collected. We propose that this requirement can be fulfilled on the basis of the so-called Burstein shift of the absorption edge [6] in semiconductors doped with impurities *of one type*.[1]

To maximize the internal light emission efficiency, the following material requirements must be fulfilled:

1. The material must be chosen in such a way that the radiative component of recombination dominates over non-radiative components.
2. The material structure must minimize the absorption of its own radiation.

This list of requirements leads to the well-known direct-gap III–V semiconductors, such as GaAs and InP. We shall present our discussion in the instance of InP:

a. The material is direct, and can provide high internal emission efficiency with the predominantly radiative component of recombination;
b. Indium has a relatively high atomic number $Z = 49$ (vs. 14 for Si and 32 for Ge), while InP has a relatively low energy of $\sim$4 eV per electron–hole pair created by the primary ionizing radiation;
c. The effective electron mass in InP is relatively small (0.08 m_0) which leads to a lower conduction band density of states and therefore higher Burstein shift for a given doping level.

The proposed detector comprises a slab of direct-gap semiconductor, such as InP, heavily doped so as to minimize the absorption coefficient for its own interband

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[1] When semiconductor is degenerately doped, the edge of absorption is blue-shifted relative to the emission edge by the carrier Fermi energy. This effect underlies the operation of semiconductor lasers.