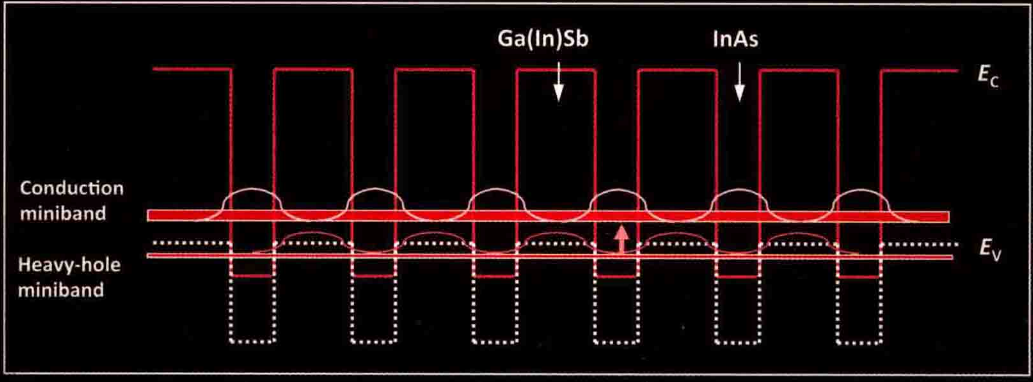
SEMICONDUCTORS AND SEMIMETALS

VOLUME 84

Advances in Infrared Photodetectors

Edited By
Sarath D. Gunapala, David R. Rhiger
and Chennupati Jagadish



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Advances in Infrared Photodetectors

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PREFACE

Although the invisible portion of the electromagnetic spectrum includes gamma rays, X-rays, and ultraviolet rays beyond the blue end of the visible spectrum and infrared rays (spanning a wide wavelength swath from $\sim$0.7 μm to $\sim$1 mm) and microwaves beyond the red end, light detectors operating in the mid- and long-wavelength infrared ranges hold a special significance. Potential applications at these wavelengths range from the mundane to the sublime. Room temperature objects glow brightest in this wavelength range. Detectors with the sharpest eyes for light at these wavelengths are ideal for a variety of ground- and space-based applications such as night vision, navigation, weather monitoring, security and surveillance, etc. In addition, they can be used to monitor and measure pollution, relative humidity profiles, and the distribution of different gases in the atmosphere. This is due to the fact that most of the absorption lines of gas molecules lie in these infrared spectral regions. The earth's atmosphere is opaque to most of the infrared rays; of its few transparent windows, the 3–5.5 μm and 8–12 μm are the most useful. Cameras operating in this wavelength range and used in ground-based telescopes will be used to see through the earth's atmosphere, image distant stars and galaxies (including those invisible to telescopes equipped with normal visible eyes), and help in the search for cold objects such as planets orbiting nearby stars. Thus, infrared detectors operating in the mid- and long-wavelength range have myriad applications.

Research in infrared photon detectors led to many new infrared detection devices, materials, and large-format infrared focal plane arrays for imaging applications. Research activities in the areas of HgCdTe, strained-layer superlattices, quantum-well infrared detectors, homo- and hetero-junction devices, quantum-dot infrared detectors, blocked impurity band (BIB) detectors, and quantum wells for far-infrared detection have been very intense over last two decades. Therefore, we collected a comprehensive review of the various topics related to the infrared photon detectors based on II–VI and III–V compound semiconductor materials. We hope this volume will provide a valuable reference for the researchers in the field of infrared detectors, related fields, and for those individuals like graduate students, scientists, and engineers who are interested in learning about these subjects.

The six chapters in volume 84 of the Elsevier's *Semiconductors and Semimetals* cover the following topics: Chapter 1 describes the development of strained layer superlattice for infrared detection from inception to focal planes; Chapter 2 discusses the progress of quantum-well infrared photodetectors (QWIPs) in the last two decades, which culminated low-cost focal planes for commercial use; Chapter 3 discuss the quantum dots for infrared detection; Chapter 4 describes the quantum-well THz detectors; Chapter 5 describes the homo- and heterojunction interfacial workfunction internal photoemission detectors from ultraviolet to infrared detection; and Chapter 6 describes the advances made in long-wavelength infrared HgCdTe detectors.

We thank all the contributors who have devoted their valuable time and effort in putting together a comprehensive volume in timely manner. We also sincerely thank Ben Davie and Paul Chandramohan of Elsevier for providing assistance and accommodating our schedule.

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CONTENTS

CHAPTER 1

Type-II Superlattice Infrared Detectors

David Z.-Y. Ting, Alexander Soibel, Linda Höglund, Jean Nguyen, Cory J. Hill, Arezou Khoshakhlagh, and **Sarath D. Gunapala**

Contents

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1. INTRODUCTION

The type-II InAs/GaSb superlattices (Sai-Halasz *et al.*, 1977) have several fundamental properties that make them suitable for infrared detection: their band gaps can be made arbitrarily small by design (Sai-Halasz *et al.*, 1978a), they are more immune to band-to-band tunneling compared with bulk material (Smith and Mailhiot, 1987; Smith *et al.*, 1983), the judicious use of strain in type-II InAs/GaInSb strained layer superlattice (SLS) can enhance its absorption strength over that of the type-II InAs/GaSb superlattice to a level comparable with HgVdTe (MCT) (Smith and Mailhiot, 1987), and furthermore, type-II InAs/Ga(In)Sb superlattices have been shown theoretically (Grein *et al.*, 1992) and experimentally (Youngsdale *et al.*, 1994) to have reduced Auger recombination. These properties generated strong interests and led to the demonstration of the first high-performance photodiodes (Fuchs *et al.*, 1997a; Johnson *et al.*, 1996) and focal plane array (FPA) (Walther *et al.*, 2005b). In the mid-wavelength infrared (MWIR), sophisticated production-ready simultaneous dual-band FPAs already exist (Rehm *et al.*, 2010; Walther *et al.*, 2007). In the long-wavelength infrared (LWIR), heterostructure superlattice detectors (Aifer *et al.*, 2010a; Gautam *et al.*, 2010; Nguyen *et al.*, 2007b; Ting *et al.*, 2009a) that effectively use unipolar barriers (Ting *et al.*, 2009a) have shown strong reduction of generation-recombination (G-R) dark current due to Shockley-Read-Hall (SRH) processes. Higher absorber doping levels afforded by immunity to tunneling has led to reduced diffusion dark current (Ting *et al.*, 2010), despite relatively short lifetimes found in existing superlattice material (Connelly *et al.*, 2010; Donetsky *et al.*, 2010; Pellegrino and DeWames, 2009). The dark current characteristics of type-II superlattice-based single element LWIR detectors are now approaching that of the state-of-the-art MCT detector. Noise measurements highlight the need for surface leakage suppression (Soibel *et al.*, 2010), which can be tackled by improved etching (Nguyen *et al.*, 2010b), passivation (Fuchs *et al.*, 1998a; Mohseni *et al.*, 1999), and device design (Aifer *et al.*, 2007; Wicks *et al.*, 2010). Large-format LWIR FPAs have been demonstrated in research laboratories (Gunapala *et al.*, 2010; Manurkar *et al.*, 2010). The continuous improvement in substrate, material quality, device design, and processing technique, coupled with better understanding of the fundamental properties, could lead to high-performance large-format LWIR focal plane arrays in the near future.

The reminder of this chapter is organized as follows: Section 2 reviews the development of the type-II superlattice infrared detectors from a historical perspective. Section 3 discusses basic properties of the type-II superlattice, largely from simple theoretical considerations. Section 4 describes the principles behind advanced superlattice infrared detectors based on heterostructure designs. Section 5 explores some aspects of device fabrication and characterization of contemporary interest. A short summary and outlook is given in Section 5. As this chapter covers only a limited set of topics, the interested readers are also referred to review articles by Bürkle and Fuchs (2002); Fuchs *et al.* (1997b), and Razeghi and Mohseni (2002), as well as the book by Rogalski (2011) for additional information.

2. HISTORICAL PERSPECTIVE

In this section, we review the development of type-II antimonide superlattice infrared detector through a historical perspective. We begin with the discovery of the broken-gap band alignment and the invention of the type-II superlattice from 1976 to 1978. We next examine the period between 1979 and mid-1990s when the concept of using type-II superlattices for infrared detection took shape, supported by theoretical and experimental works. The following period, between 1996 and 2005, saw the first high-performance detectors and the demonstration of the first focal plane array. Finally, rapid growth of the field occurred between 2005 and the present time (2010), with the emergence of detectors based on advanced heterostructure designs, and significant progress in focal plane array technology development.

2.1. Type-II superlattice and the broken-gap band alignment

The year 1977 marked the birth of the type-II superlattice with the publication of a seminal paper by Sai-Halasz *et al.* (1977) from the IBM T. J. Watson Research Center. In the paper, the authors proposed and analyzed theoretically a new type of bilayer semiconductor superlattice in which the lower conduction band (CB) edge is located in one material, whereas the higher valence band (VB) edge is in the other. In this kind of superlattice (Fig. 1.1), the wave functions of the lowest conduction subband and the highest valence subband are localized in the two different

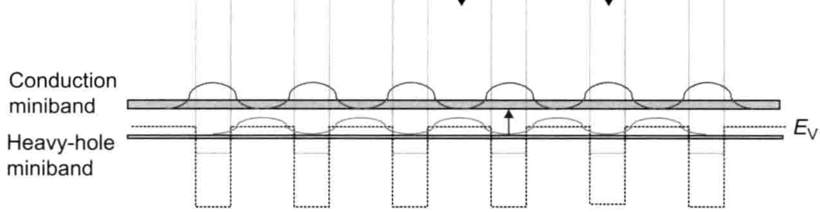

FIGURE 1.1 Schematic illustration of an InAs/Ga(In)Sb type-II broken-gap superlattice showing the spatial separation of the conduction band and the heavy-hole band wave functions. The infrared transition is indicated by an arrow.

host semiconductors (spatially delocalized), and therefore, the positions of the CB edge and the VB edge can be, to first order, tuned independently. It was suggested that this type of superlattice could be realized by using the closely lattice-matched semiconductor pairs of InAs/GaSb or InGaAs/GaSbAs. It was also pointed out in particular that based on the known electron affinity values, the CB edge of InAs was expected to be 0.14 eV lower than the VB edge of GaSb (now called the broken-gap band alignment), and this would lead to an interesting behavior since the superlattice CB and VB states are close in energy and could therefore interact. This new type of superlattice, in which the band gaps of the two host semiconductors are in either a staggered or a broken-gap alignment, was later referred to as "type II" (Sai-Halasz *et al.*, 1978b) to distinguish it from the "type I" superlattice originally proposed by Esaki and Tsu (1970), in which the host band gaps are in a nested alignment.

The key feature that enabled the concept of the type-II superlattice was the broken-gap band alignment between InAs and GaSb. W. Frensley first noticed the very unusual band alignment between InAs and GaSb in the course of his PhD thesis research under the direction of H. Kroemer at the University of Colorado (Frensley and Kroemer, 1977). The IBM Group came to the realization around the same time. Noting the unusually large electron affinity of InAs, Sai-Halasz *et al.* (1977) predicted the broken-gap band lineup between InAs and GaSb based on the electron-affinity rule (Anderson, 1962), which, though later found to be inadequate (Niles and Margaritondo, 1986), happened to hold up well in this case. The InAs-GaSb broken-gap band lineup was also predicted through the means of more sophisticated theoretical methods, as reported by Harrison (1977) using linear combination of atomic orbital (LCAO) theory and by Frensley and Kroemer (1977) using pseudopotential theory. Although Harrison did not attach any special significance to the broken gap alignment (it was one of many values tabulated in a comprehensive study of heterojunction band offsets), Frensley and Kroemer (1977) pointed out that among all the predicted band offsets, perhaps the most interesting is that for the InAs-GaSb system, in which the InAs conduction band edge was predicted to be below that of the GaSb valence band edge. They speculated that this band lineup could lead to very interesting transport properties such as interband tunneling. Indeed, interband tunneling was observed experimentally by Sakaki *et al.* (1977) from IBM in a study of InGaAs-GaSbAs heterojunction diode current–voltage ($I-V$) characteristics.

In the original study of type-II superlattices, Sai-Halasz *et al.* (1977) used Kane's two-band model (Kane, 1957) to treat the interaction between the InAs conduction band and the GaSb light-hole band while ignoring the heavy-hole band. In the following year, Sai-Halasz and Esaki, in collaboration with Harrison, reexamined the band structure of InAs-GaSb superlattices using LCAO theory (Sai-Halasz *et al.*, 1978a). They found that while superlattices with thin InAs and GaSb layers have well-defined energy band gaps and act as semiconductors, those with thick layers behave as semimetals. This means that the band gap of the InAs/GaSb superlattice can be made arbitrarily small — smaller than that of either InAs or GaSb. The IBM Group then proceeded to demonstrate this trend of decreasing band gap with increasing layer thickness experimentally (Sai-Halasz *et al.*, 1978b) using a set of molecular beam epitaxy (MBE) grown samples that showed measured band gaps ranging from 265 to 360 meV at 10 K. Correlation with theoretical calculations also established the InAs CB edge to be at approximately 150 meV below the GaSb VB edge, a value that is still used today.

In the literature, "type-II broken gap" is sometimes referred to as "type III" to distinguish it from "type-II staggered" (Davies, 1998; Dragoman and Dragoman, 2002; Sze and Ng, 2007). However, the term "type III" is often used in the infrared detector literature to refer to superlattices consisting of alternating layers of an inverted band structure zero-gap semiconductor and a normal wider gap semiconductor, such as the HgTe/CdTe superlattice (Kinch, 2007). Kroemer advocates using only the descriptive names of nested (or straddling), staggered, and broken gap (or misaligned) and doing away with numerical designation of types I, II, and III altogether. We use "type-II broken gap" or simply "type II" in this work.

2.2. Superlattices for infrared detection

The concept of using superlattices for infrared detection started in the HgCdTe (MCT) material system. Although a practical MCT superlattice infrared detector has not been realized, the idea had a major influence on the development of antimonide superlattice infrared detectors. Schulman and McGill (1979a,b) first proposed the use of the CdTe/HgTe superlattice as an infrared material, with possible uniformity advantages over the MCT alloy. In one of their papers, Schulman and McGill (1979a) pointed out that the InAs/GaSb superlattice should have similar band gap properties as the CdTe/HgTe system, but they also expressed the concern that the size of the optical matrix element may be inadequate because electron and hole wave functions of the states involved in the infrared transitions are spatially separated in a type-II superlattice. Later, Smith *et al.* (1983) revisited the theory of CdTe/HgTe superlattices and identified some key advantages of superlattices over bulk materials for infrared detection: (1) the cutoff wavelengths of MCT superlattices have weaker dependence on composition than the MCT alloy and are, therefore, less susceptible to variations due to compositional fluctuation, (2) superlattices have reduced p-side diffusion current due to the larger electron mass, and (3) superlattice tunneling lengths are shorter than for MCT alloys with the same band gap and therefore have reduced band-to-band tunneling. These properties are found in the InAs/GaSb superlattice as well. Regarding the concern for possible weak oscillator strength in type-II superlattices (Schulman and McGill, 1979a), Chang and Schulman (1985) calculated optical properties of InAs/GaSb superlattices. They found that in a (*M*,*N*)-InAs/GaSb superlattice (each period consisting of *M* monolayers of InAs and *N* monolayers of GaSb), for sufficiently large *M* and *N* (>10 or more), the oscillator strength of optical transitions is approximately proportional to $1/MN$, decreasing rapidly with layer thickness. In a review article, Kroemer (2004) described this in a simple intuitive manner. Since electron and hole wave functions are separately localized in InAs and GaSb layers, respectively, they overlap each other mostly near the heterointerfaces. Hence, to first order, the optical absorption is proportional to the number of interfaces rather than to the superlattice thickness. This means that much of the volume is optically inactive in InAs/GaSb superlattices with long periods (which are needed to achieve small band gaps for long wavelength infrared detection).

So, how can we reduce the superlattice period to enhance oscillator strength without increasing the energy band gap? To address this issue, Smith and Mailhiot (1987) proposed the type II InAs/GaInSb strained layer superlattice (SLS) infrared detector. Smith and Mailhiot considered a free-standing InAs/$Ga_{0.6}In_{0.4}Sb$ SLS in which the InAs and GaInSb layers are under tensile and compressive strain, respectively. As illustrated in Fig.1.2, the effect of strain is to lower the InAs CB edge and raise the GaInSb heavy-hole (HH) band edge, which makes both the InAs CB quantum well and the GaInSb HH band quantum well deeper. Consequently, one could employ narrower quantum wells without increasing the superlattice band gap. The SLS has larger optical matrix elements than the InAs/GaSb superlattice. Although the optical matrix element of the type-II SLS is still smaller than that in bulk MCT, its absorption coefficient is comparable to that of MCT because of the higher joint density of states. The electron effective mass for a 10-μm cutoff SLS is $\sim 0.04\ m_0$ ($0.0088\ m_0$ for MCT of comparable cutoff wavelength), which is large enough to reduce band-to-band tunneling and still small enough to provide good electron mobility. It was suggested that since electron mobility is much higher than hole mobility, *n* on *p* diodes should be used for infrared detection. Smith and Mailhiot also noted that GaSb would be a good substrate on which to grow the InAs/GaInSb superlattice. Miles *et al.* (1990) experimentally demonstrated LWIR absorption in InAs/GaInSb strained layer superlattices.