Terahertz absorption in InAs/GaSb type-II superlattices

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Abstract—We theoretically demonstrate that it is possible to realize terahertz (THz) fundamental band-gap in InAs/GaSb type-II superlattices (SLs). The presence of such THz band-gap can result in a strong cut-off of optical absorption at THz bandwidth for relatively high-temperatures. This study is pertinent to the application of InAs/GaSb type-II SLs as optoelectronic devices such as THz photodetectors.

I. INTRODUCTION AND BACKGROUND

Terahertz (10\textsuperscript{12} Hz or THz) is the most scientifically rich area of the electromagnetic (EM) spectrum\textsuperscript{1}. The THz wave (or T-ray) technology is of great potential to impact many interdisciplinary fields such as telecommunication, biological science, pharmaceutical technology, nanotechnology, to mention but a few. The realization of T-ray sources and sensors has been an important research field in optics and optoelectronics since 1980s\textsuperscript{2}. From a physics point of view, for the generation and detection of THz radiation it is necessary to realize a material system in which the fundamental energy gap is around THz photon energy. Thus, THz generation and detection can be achieved through electronic transition accompanied by the emission and absorption of THz photons. Here we propose to employ InAs/GaSb based type-II Superlattice (SL) systems as THz band-gap materials. In an InAs/GaSb type-II SL, the electrons and holes are separated spatially in different material layers\textsuperscript{3} so that the energy gap between the confined electron states in the InAs layer and the confined hole states in the GaSb layer can be tuned artificially by simply varying the sample growth parameters such as the widths of the InAs and GaSb layers. Thus, by band-gap engineering, we can realize a SL system in which the fundamental energy gap between the valence miniband in the GaSb layer and the conduction miniband in the InAs layer is at THz bandwidth. On the basis of such structures, THz optoelectronic devices can be designed, tested and realized.

II. THEORETICAL APPROACH AND RESULTS

A. THz fundamental band-gaps

In this study we generalize the usual Kronig-Penney model\textsuperscript{4} to calculate the electronic miniband structure of InAs/GaSb type-II SLs. From this calculation, we can obtain the wavefunction $\psi_{nk}(z)$ and energy spectrum $E_n(k_z)$ for an electron ($j = e$) or a heavy-hole ($j = h$) in the $n$th miniband in the SL, with $k_z$ being the SL wavevector along the growth direction. The material parameters used in the calculation are documented in Ref. [5]. In Fig. 1, we show the fundamental band-gap between the bottom of the lowest electron miniband in the InAs layer and the top of the highest heavy-hole miniband in the valence band ($k_z = 0$) in the GaSb layer as a function of the InAs (GaSb) layer width at a fixed GaSb (InAs) well thickness. It is found that there are two sets of growth parameters which can be used to achieve THz band-gap in InAs/GaSb SLs. When the InAs/GaSb layer widths are about 8.5/2.8 or 6.1/7.9 nm, the fundamental band-gap $E_g = E_e^0(0) - E_h^0(0)$ is of the order of THz and can be tuned by adjusting the InAs/GaSb layer widths. The band-gap $E_g$ decreases with increasing the InAs and /or GaSb layer width, because the energy of the electron miniband in the InAs layer decreases with increasing the InAs layer thickness and that of the heavy-hole miniband in the GaSb varies in the opposite direction. We also find that in these sample structures, the energy separations among the electron and hole minibands in different layers are larger than 100 meV, i.e., they are in the mid-infrared bandwidth. It implies that in an InAs/GaSb type-II SL, THz emission and absorption can be achieved via type-II transition channels.

Fig. 1: Band-gap energy between the bottom of the lowest electron miniband in the InAs layer and the top of the highest heavy-hole miniband in the GaSb layer as a function of GaSb (InAs) layer width $L_B$ ($L_A$) at a fixed InAs (GaSb) layer width, shown in panel (a) [(b)].
B. Optical absorption spectrum

We now consider that an electromagnetic (EM) field, which is polarized linearly along the growth-direction of a SL, is applied to the SL system. The electronic transition rate induced by electron and hole interactions with the radiation field can be calculated by using Fermi’s golden rule. Using the semi-classic Boltzmann equation as the governing transport equation to study the response of the carriers in a SL to the applied radiation field, the energy-balance equation\(^6\) can be derived on the basis of the Boltzmann equation. We then can obtain two energy-balance equations, respectively, for an electron and a hole and, from them the total electronic energy transfer rate due to electron-hole-photon coupling. With the total electronic energy transfer rate, the optical absorption coefficient induced by electron and hole interactions with the radiation field can be calculated. Thus, the inter- and intra-band transitions can be included within the calculation.

In an undoped InAs/GaSb type-II SL, the presence of the radiation field can pump electrons in the valance band in the GaSb layer into the conduction band in the InAs layer. Such process induces photo-excited carriers whose transitions contribute mainly to the optical absorption in the SL. In this study, we assume that the photo-excited electron and hole densities in undoped SLs is about \( n_e = n_h = 2.0 \times 10^{17} \text{ cm}^{-3} \) per SL cell, which satisfies the condition of the charge-neutrality. Because in an InAs/GaSb SL the electron and heavy-hole have different effective masses, the non-equilibrium chemical potentials induced by the presence of photo-excited carriers for electrons and holes are different.

![Fig. 2: Optical absorption coefficient at a fixed InAs (GaSb) layer width \( L_A \) (L\(_B\)) for different layer widths \( L_B \) (L\(_A\)) shown in panel (a) [b]. The results are shown for \( T=35 \text{ K} \) and \( \alpha_\text{opt} = \frac{c}{\varepsilon_0} \sqrt{\frac{e}{\hbar c}} \) with \( c \) and \( \varepsilon_0 \) being respectively the light-speed in vacuum and the dielectric constant of free space.](image)

Because in an InAs/GaSb type-II SL the energy spacing among the electron/hole minibands is much larger than the THz energy, the THz optical absorption is achieved mainly via type-II transition channel, namely through the inter-layer transition between the electron miniband in the InAs layers and the heavy-hole miniband in the GaSb layers. The dependence of the optical spectrum on the InAs/GaSb layer widths is shown in Fig. 2 at \( T=35 \text{ K} \). Because of a strong type-II optical transition in an InAs/GaSb SL, a sharp cut-off of the optical absorption spectrum can be observed at THz frequencies around the band-gap \( E_g \). With increasing the InAs and/or GaSb layer widths, the red-shift of the cut-off absorption can be observed. The rather wide absorption spectrum seen here is induced mainly by the presence of the dispersed miniband structures in a SL. We find that a more efficient THz absorption can be observed for samples with wider InAs well widths. For example, a stronger absorption (about a factor of 2) at 1 THz can be seen for a sample with the well widths 8.5/3.0 nm than that with the well widths 6.3/7.9 nm. More pronounced cut-off of the THz absorption can be achieved for samples with smaller band-gaps. Furthermore, we find that the strength of THz absorption via type-II optical transition in InAs/GaSb SLs depends strongly on temperature. A marked red-shift of the cut-off absorption can be observed with increasing temperature. Such a red-shift is mainly induced by the well known Pauli blockade effect. We notice that for type-II optical transitions in a SL, there are two different mechanisms for direct carrier-photon interaction through optical absorption scattering. One is required by the momentum and energy conservation laws during a scattering event (Mechanism I). Another is caused by the Fermi-Dirac distribution functions for electrons and holes, which reflects a fact that optical transition can be achieved via exciting the electrons in the occupied states in the hole minibands in the GaSb layer into the empty states of the electron minibands in the InAs layer (Mechanism II). We find that for typical InAs/GaSb type-II SLs, the Mechanism I results in a cut-off in optical absorption at relatively high-temperatures (\( T>30 \text{ K} \)), whereas the Mechanism II is responsible for the optical absorption cut-off at relatively low-temperatures (\( T<30 \text{ K} \)). More interestingly, we note that for an InAs/GaSb type-II SL, a sharper cut-off in THz absorption can be observed at relatively high-temperatures. This implies that InAs/GaSb type-II SLs can be applied as THz photodetectors working at relatively high-temperatures for various applications. It has been realized experimentally that when the InAs/GaSb layer widths in a short-period SL are around 2.0/2.5 nm, the SL systems can be used as uncooled mid-infrared photodetectors working at 3–5 \( \mu \text{m} \) bandwidth\(^7\). Thus, we hope that the relatively long-period InAs/GaSb type-II SLs proposed here can be applied as THz photodetectors working at relatively high-temperatures for various applications.

**REFERENCES**