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Carrier transport and optical properties in GaAs far-infrared/terahertz mirror structures

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Abstract

We report on detailed carrier transport and optical properties in doped/undoped GaAs far-infrared (FIR)/terahertz (THz) mirror structures for GaAs-based FIR/THz device application. By the aid of variable magnetic field Hall and Shubnikov de Haas measurements, we have analyzed the carrier concentration, mobility and scattering times. It is found that ionized impurity scattering is the dominant scattering mechanism in the GaAs FIR/THz mirror structures. We investigate numerically the energy flux along the mirror depth and the reflection of the mirror structure. The experimental FIR/THz reflection and transmission spectra demonstrate the reliability of the optical analysis.

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1. Introduction

Far-infrared (FIR)/terahertz (THz) electromagnetic radiation and detection have received more and more attention nowadays, due to their potential applications in various areas, such as biomedical imaging, quantum computing, space astronomy, spectroscopy, and communications [1–4]. The typical examples of FIR/THz semiconductor devices with mature GaAs material are quantum cascade lasers (QCLs) [5] and homojunction internal photoemission FIR detectors [6]. It is well known that resonant-cavity-enhanced (RCE) structures have been widely employed to improve the performance of semiconductor devices. The RCE structures are simply formed by sandwiching devices between a pair of mirrors, and proper design of these mirrors (or reflectors) is essential. Previous reports on the application of resonant cavities concentrate mainly on the near- and mid-infrared semiconductor devices [7], where distributed Bragg reflectors (DBRs) have shown excellent effect and structure popularity.

Nevertheless, there is little discussion about the RCE structures for FIR/THz semiconductor devices. Due to the long wavelength and free carrier absorption nature in the FIR/THz region, it is much more complex to design FIR/THz mirrors, in comparison with the near- and mid-infrared counterparts. The following three conditions should be considered simultaneously: (i) the mirror materials must be well lattice-matched to avoid the introduction of defects into the device layers; (ii) the mirrors should have high reflectivity and well-matched phase; and (iii) the performance of the RCE scheme depends critically on the realization of a low loss mirror. Recently, we have proposed a RCE structure for GaAs homojunction FIR detectors [8]. The top mirror of the RCE structure is a native semiconductor/air interface for simplicity and the bottom mirror consists of doped/undoped GaAs multilayers. Such doped/undoped GaAs FIR/THz mirror structures have demonstrated a satisfactory effect. The resulting quantum efficiency in the GaAs FIR detector cavity is three times of the normal one without the RCE structure [9].

The better understanding of the doped/undoped GaAs FIR/THz mirrors is helpful for the application of such a mirror concept in other kinds of GaAs-based FIR/THz semiconductor devices, taking advantages of the mature and uniform material

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as well as monolithic integration technology. The potential application includes the extension of vertical-cavity surface emitting QCLs [10] to FIR/THz region with GaAs. In this paper, we have carried out a detailed electrical and optical investigation on this kind of doped/undoped GaAs FIR/THz mirror structure. Through variable magnetic field Hall and Shubnikov de Haas (SdH) measurements, we obtain the information of carrier concentration, mobility and scattering times. The energy flux along the mirror depth and the reflection of the mirror structure have been investigated numerically, and experimental FIR/THz reflection and transmission spectra are measured to verify the reliability of the optical analysis.

2. Experimental details

The doped/undoped GaAs multilayer FIR/THz mirror structures were grown by molecular beam epitaxy (MBE) on semi-insulating GaAs substrates [9]. The sample consists of three GaAs layers: a highly doped top layer (*n* doped by Si, 2×10^{18} cm^{-3}) with a thickness of 3000 Å followed by an intrinsic undoped layer (1.45 μm) and a thick highly doped bottom layer (1.80 μm, *n* doped by Si, 3×10^{18} cm^{-3}). The magnetic field dependent Hall and SdH measurements were performed in the Van der Pauw configuration by a set of Keithley Hall measurement system, including a 220 programmable current source, 2182 nanovoltmeter and 7001 switch system with a 7065 Hall card [11]. The ohmic contacts were fabricated by alloying indium on the surface of the GaAs multilayer structure. The sample was immersed in a ^{4}He cryostat system equipped with a 15 Tesla Oxford Instruments superconductive magnet, where the measured temperature can be down to 1.6 K. The magnetic field reading accuracy was better than 1%. The FIR/THz reflection and transmission spectra were performed on a Nicolet Nexus 870 Fourier transform infrared spectrometer with a deuterated triglycine sulfate (DTGS) polyethylene detector, solid substrate beamsplitter and infrared globar source. The reflection measurements were taken with near-normal incidence geometry (less than 10° incidence angle). The optical measurements were made with a resolution of 2.0 cm^{-1}.

3. Results and discussion

3.1. Magnetic field dependent hall effect

Fig. 1(a) presents the magnetic field (*B*) dependence of the experimental results (scatters) at 6.0 K, in the form of conductivity components $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$, for the doped/undoped GaAs FIR/THz mirror structure. Here the variable magnetic field Hall measurements were performed in the magnetic field range from 0 to 7 Tesla because of the presence of the SdH oscillations at higher magnetic fields. The experimental fact that we have observed negative values of $\sigma_{xy}(B)$ throughout the magnetic field reflects the *n*-type nature of the measured sample, which is in agreement with our MBE design of the FIR/THz mirror structure. It should be noted that traditional fixed magnetic field Hall measurements only give average carrier concentration and mobility. In combination with mobility spectra analysis (MSA) procedures [12], the variable magnetic field Hall measurements, as shown in Fig. 1(a), can yield the distribution of electron mobility and extract the transport parameters of all carrier species present within the sample that are contributing to the conducting processes [11–13].

In the MSA approach, discrete carriers are generalized by a conductivity concentration function which spreads over a continuous mobility (μ) range. The two conductivity tensors are given by [12]:

$$\sigma_{xx}(B) = \frac{\rho(B)}{\rho^2(B) + B^2R_H^2(B)} = \int_0^\infty \frac{s^p(\mu) + s^n(\mu)}{1+\mu^2B^2}\,\mathrm{d}\,\mu$$
$$\sigma_{xy}(B) = \frac{BR_H(B)}{\rho^2(B) + B^2R_H^2(B)} = \int_0^\infty \frac{(s^p(\mu) - s^n(\mu))\mu B}{1+\mu^2B^2}\,\mathrm{d}\,\mu \tag{1}$$

where $R_H(B)$ and $\rho(B)$ are the experimental magnetic field dependent Hall coefficient and resistivity, respectively, and $s^p(\mu)$ and $s^n(\mu)$ are the hole and electron conductivity concentration functions, respectively. The MSA would transform the above experimental magnetic field dependent Hall data into the dependence of the conductivity concentration function on the mobility, in which each kind of carrier contributing to the total conductivity appears as a separate peak at a given mobility. Fig. 1(b) shows the corresponding mobility spectrum obtained via the MSA procedures from the experimental $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$. The solid curves in Fig. 1(a) are the calculated $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ obtained using the carrier concentrations and mobility distributions in Fig. 1(b), which show good agreement with the experimental data.

In Fig. 1(b), there is only one electron peak in the mobility spectrum by the MSA, revealing only one electron species there. This is reasonable, since there is only one kind of *n*-type high doping concentration (2–3×10^{18} cm^{-3}) in the studied GaAs FIR/THz mirror structure. The peak corresponds to an effective value of the highly doped GaAs layers, which dominate the conductivity. The contributions of the undoped GaAs layer and semi-insulating GaAs substrate to the

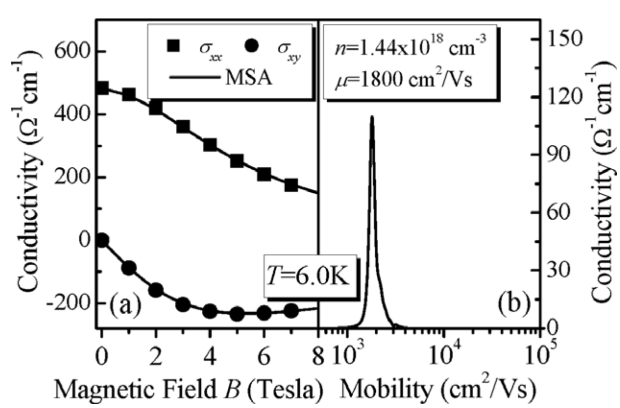

Fig. 1. (a) Experimental conductivity tensor components $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ as a function of magnetic field *B* for the doped/undoped GaAs multilayer FIR/THz bottom mirror structure at 6.0 K. The solid curves are the calculated results by using MSA procedures. (b) The yielded mobility spectrum.