Comparative study on calculated terahertz absorption spectra of different heterostructure materials with external magnetic field

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Abstract

Room temperature operation and frequency tunability are attractive advantages of terahertz (THz) detectors based on the two-dimensional electron gas (2DEG) in the heterostructure material with external magnetic field. This work compared absorption spectra of four typical heterostructure materials (AlGaN/GaN, InAlN/GaN, AlGaAs/GaAs and SiGe/Si) with the nonlocal magnetoconductivity model at ambient and cryogenic temperatures in the frequency range 0–5 THz. The GaN based materials have the highest absorption amplitude, while the AlGaAs/GaAs material owns the largest frequency shift as the magnetic field increases up to 10 tesla, although superconducting magnets at cryogenic temperature are usually employed to provide that high magnetic field. The numerical results showed that the absorption properties (amplitude and frequency) could be further optimized by other parameters, such as the period and filling factor of the grating coupler, and the barrier thickness.

1. Introduction

Terahertz (THz) detectors are the key component in the THz application system. As the thermal and broadband detector, bolometer [1] cooled at liquid helium temperature has the relatively high sensitivity, but it is bulky and expensive and the response it slow (several milliseconds). Golay cell [2] and the pyroelectric detector [3] work at ambient temperature with a response time of a few ten milliseconds. The responsivity and noise equivalent power (NEP) is in the order of $10^5$ V W$^{-1}$ and $10^{-10}$ W/Hz$^{1/2}$, respectively. As the electronic and narrowband detector, the Schottky barrier diode [4] has the response time in the order of several nanoseconds, while the responsivity drops greatly if the frequency is higher than 1 THz. Room temperature MOSFET detectors [5] based on the silicon material which are placed in the array form could ameliorate the detection sensitivity. Further improvements of the detection frequency and response time are difficult due to the low electron concentration and electron mobility in the conductive channel. With the development of molecular beam epitaxy and modulation doping techniques, heterostructure materials with high electron density and elevated electron mobility have been successfully fabricated, including the III–V and IV–IV group. THz detection based on properties of the two-dimensional electron gas (2DEG) in heterostructure materials has been well explained and demonstrated in both resonant and broadband modes [6, 7]. This type of THz detectors has advantages of low cost, compact size, high sensitivity, frequency tunability and array operation at room temperature. For example, the NEP value of the high electron mobility transistor (HEMT) based on the AlGaN/GaN material has achieved $10^{-9}$ W/Hz$^{1/2}$ at 0.937 THz [8]. New materials like graphene with ultra-high electron mobility have found applications as the active layer in the FET structure for THz detection, but the fabrication of high quality graphene FET is still difficult [9–11].

For room temperature detection with heterostructure materials in the resonant region, the electron concentration and electron mobility should be as high as possible. With dense electrons under metallic gratings [12, 13], the interaction of collective oscillation of electrons with the incident THz electromagnetic field will be strengthened. High mobility electrons own longer phenomenological relaxation time, although various scattering mechanisms become significant and therefore obstacle this effect at elevated temperature. In order to
achieve frequency tunability in the detection process, a bias voltage was traditionally applied on the grating surface to alter the concentration of the underlying electrons and therefore the electromagnetic model of 2DEG layer. Depending on the sign and amplitude of the bias voltage and the material type, the observed resonant frequency could be altered more or less. The other convenient method to change the resonant frequency was realized by introducing the static magnetic field along the direction perpendicular to the 2DEG plane, where the magnetoplasmon-polaritons (MPPs) modes will dominate in the detector response [14, 15]. Both the amplitude and frequency were influenced by the strength of magnetic field.

Properties of MPPs in heterostructure materials were evaluated in two different ways. One is the complex dispersion equation established on Maxwell equations and associated boundary conditions between adjacent layers according to the structural and material parameters in each layer [16]. The knowledge of effective filling factor in the periodic grating layer is the precondition to derive the explicit form of complex frequency. The real part of the calculated frequency stands for the resonant frequency, while the imaginary part represents the loss nature of each MPPs mode. Normally dispersion equations were usually solved numerically at only two extreme cases (gated and ungated 2DEG). The other method to evaluate characteristics of MPPs was acquired by directly observing the absorption spectrum. At discrete resonance frequencies, the absorption amplitude and peak width reflect the interaction strength of 2D plasmon with the THz radiation and loss nature of each mode, respectively. In the measurement, the transmission, reflection or absorption spectrum was conveniently obtained in the standard Fourier transform infrared spectroscopy (FTIR) and THz time domain spectroscopy (TDS) systems [12, 17, 18].

From the aspect of materials, GaN based heterostructures possess the high electron concentration even without modulation doping due to strong spontaneous and piezoelectric polarizations. The AlGaN/GaN material has the minimum lattice mismatch and low effective mass, and the electron concentration in the level of $10^{16} \text{m}^{-2}$ could be achieved with the aid of modulation doping in the growth process. The IV-IV group SiGe/Si material has advantages of low price and mature silicon production technology, and its electron concentration and mobility are in the moderate level via modulation doping. The detection property of each material should be studied systematically in consideration of various parameters at ambient and cryogenic temperatures, such as the mobility, concentration and effective mass of electrons, the period and filling factor of the grating, and the barrier thickness in the heterostructure.

In order to calculate accurately the transmission, reflection or absorption spectrum, the electromagnetic model for the 2DEG layer in the presence of external magnetic field should be known in priority. The local Drude type magnetoconductivity model neglected the effect of the plasmon wavevector selected by the grating period [19]. Moreover, previous simulations results for the AlGaN/GaN material at cryogenic temperature demonstrated that the local model fails in the consideration of the frequency splitting effect of the MPPs mode as well as the high order cyclotron resonance harmonics (CRHs), which possibly appeared as resonance peaks in absorption spectrum at specific values of magnetic field [16]. Therefore, the magnetoconductivity tensor of the 2DEG layer with nonlocal corrections draws a more complete picture, where the MPPs modes, cyclotron resonance and its higher order harmonics are included.

The work compared and optimized absorption spectra of four typical heterostructure materials (AlGaN/GaN, InAlN/GaN, AlGaAs/GaAs and SiGe/Si) particularly at room temperature for THz detection by using the nonlocal 2DEG magnetoconductivity model. The remainder is organized as follows. Section 2 presented the general method to calculate the absorption spectrum in a multilayer system with grating coupler and this method is realized in a homemade numerical code in the frequency range 0–5 THz. Based on the calculation method, absorption spectra for the four materials were compared at the same magnetic field up to 10 T in section 3. Properties and applicability of each material were discussed according to the absorption amplitude and resonant frequency. Parametric influences of the grating period and filling factor, and the barrier thickness on absorption spectra were also evaluated quantitatively. The conclusion was given in section 4.

2. Methods to calculate the absorption spectrum

The model of the 2DEG layer influences the calculation accuracy of the absorption spectrum. The nonlocal magnetoconductivity tensor in function of the frequency, wavevector and magnetic field was introduced firstly to represent the electromagnetic behaviour of the 2DEG layer under the influence of magnetic field. For a multilayer system with periodic grating on top, the coupled wave method (CWM) [20] was utilized to find the wavevector along z axis and the electromagnetic field in the interleaved grating/air layer along x axis. Finally, the absorption spectrum was obtained based on the transfer matrix method which associates the electric and magnetic field components in each layer.

Figure 1 shows the five-layer calculation model of the heterostructure material under the external static magnetic field. Taking the AlGaN/GaN material for example, AlGaN is the barrier layer, GaN is the substrate...
material and the 2DEG layer is located at the interface between them. The THz radiation was incident normally from the semi-infinite upper air (layer 0) and its electric field was along x axis. The grating (layer 1, metal strip width $W$) with a period ($L$) of several microns causes the THz field to be scattered with both propagating (scattering order $n = 0$) and evanescent components ($n \neq 0$). The propagating reflected part of the THz wave will be detected in the upper air. After passing through a thin barrier (layer 2, thickness $d$) and reaching the 2DEG sheet (layer 3, zero thickness), the THz radiation will interact and exchange energy with the collective oscillation of electrons (plasmons). The substrate (layer 4) was assumed to be semi-infinite, where the propagating transmitted THz wave will be characterized.

2.1. Nonlocal 2DEG model
The semi-classical 2DEG magnetoconductivity tensor describing the electromagnetic and transport properties of the 2DEG layer in the $x$-$y$ plane under the excitation of magnetic field ($B$) was expressed by [15]

$$
\sigma(\omega, k, B) = \begin{bmatrix}
\sigma_{xx} & \sigma_{xy} \\
\sigma_{yx} & \sigma_{yy}
\end{bmatrix}
$$

where $\omega$ is the angular frequency, and $k$ is the plasmon wavevector dependent on the grating period at normal incidence.

The four tensor elements with nonlocal correction terms were given explicitly by [16]

$$
\sigma_{xx} = \frac{2Ne\mu}{X^2} \sum_{n=-\infty}^{\infty} \frac{j^n j'_n(X)}{1 + j(n\omega_c - \omega)\tau}
$$

$$
\sigma_{yy} = \frac{2Ne\mu}{X} \sum_{n=-\infty}^{\infty} \frac{j^n j'_n(X) j'^2_n(X)}{1 + j(n\omega_c - \omega)\tau}
$$

$$
\sigma_{xy} = -\sigma_{yx} = -\frac{2Ne\mu}{X} \sum_{n=-\infty}^{\infty} \frac{n j_n(X) j'_n(X)}{1 + j(n\omega_c - \omega)\tau}
$$

where $N$ is the electron sheet concentration, $\mu$, $e$ and $\tau$ is the corresponding mobility, charge and relaxation time of electrons and they are related by the electron effective mass as $\mu = e\tau/m^*$, $X = kv_F/\omega_c$ is the nonlocal parameter to evaluate the influence degree of the nonlocal items, where $\omega_c = 2\pi f_c = eB/m^*$ is the cyclotron frequency, and $v_F = h\sqrt{2\pi N}/m^*$ is the Fermi velocity with $h$ the reduced Planck constant. $j_n(X)$ and $j'_n(X)$ stand for the $n$-order Bessel function of the first kind and its first order derivative, respectively.

2.2. Coupled wave method
The grating (layer 1) is periodic in the $x$ axis, and therefore the effective relative permittivity could be equivalently modelled by its Fourier component in a spatial period $L$ as

$$
\varepsilon_{\alpha}(\omega) = \frac{1}{L} \int_{0}^{L} \varepsilon_0(x|\omega) e^{-j\frac{2\pi x}{L}} dx
$$

Using the effective permittivity, the second-order wave function in the grating layer (thickness $t$) could be solved numerically after truncating the maximum order of scattered waves to a specific value within a convergence criterion. The $z$-components of the wavevector for each scattered wave in the grating region constitute the eigenvalues of the wave function. Therefore, the electric and magnetic field in the grating layer could be expressed based on the calculated wavevectors.
The absorption spectrum was implemented in the Matlab program. The four materials were compared in regard to the established 2DEG magnetoconductivity model and the CWM method, the calculation of the parameter $\mu$ was given at room temperature. The grating period $L$ was set at $0.75\text{ nm}$ to have relatively strong scattered waves under the condition that the metal conductivity was $200\text{ nm}$. In the experiment, the grating was realized by the technique of electron beam lithography. For semiconductor layers, static dielectric constants were assumed in the calculation, and hence no dielectric losses were considered. At each magnetic field and grating period, the 2DEG magnetoconductivity was updated and incorporated into the calculation program by sweeping the frequency.

### 3. Results

Based on the established 2DEG magnetoconductivity model and the CWM method, the calculation of the absorption spectrum was implemented in the Matlab program. The four materials were compared in regard to the detection sensitivity and frequency tunability in the frequency range 0–5 GHz. The optimization process of absorption spectra for the AlGaN/GaN and AlGaAs/GaAs materials was also discussed.

### Table 1. Parameters of the four heterostructure materials.

| Material          | $n^2/m^*_{0}$ | $N(10^{18}\text{m}^{-3})$ | $L(\mu\text{m})$ | $W/L$ | $d(\text{nm})$ | $\mu(\text{m}^2/\text{Vs})$ |
|-------------------|---------------|--------------------------|-----------------|--------|----------------|----------------|
| AlGaN/GaN         | 0.22          | 12                       | 2.2             | 0.75   | 25             | 0.2            |
| InAlN/GaN         | 0.22          | 12                       | 1.55            | 0.75   | 10             | 0.11           |
| AlGaAs/GaAs       | 0.063         | 1                        | 1.0             | 0.75   | 25             | 0.8            |
| SiGe/Si           | 0.19          | 5                        | 1.3             | 0.75   | 25             | 0.3            |

Other layers were assumed to be isotropic and homogeneous, and hence $z$-components of the wavevector in the propagating direction were directly given by

$$k_{zm} = \sqrt{\varepsilon(\omega) \frac{\omega^2}{c^2} - k^2_{x0}}$$

(6)

where $c$ is the light speed, and $\varepsilon(\omega)$ is the relative permittivity in the layer. $k_{xm} = 2\pi n/L$ is the $x$-component of the wavevector for the $n$-order scattered wave.

#### 2.3. Transfer matrix method

For TM polarized THz radiation, the $y$ component of the magnetic field ($H_y$) was conveniently chosen as the unknown variable and the electric field components ($E_x$ and $E_z$) could be automatically calculated through $H_y$ according to Maxwell equations. The magnetic field in each layer was regarded as the combination of different scattered waves

$$H_y(\omega, k) = \sqrt{\mu_0} \sum_{n=-\infty}^{\infty} e^{jk x} [A_n e^{-jk z} + B_n e^{jk z}]$$

(7)

where $\varepsilon_0$ and $\mu_0$ is the corresponding permittivity and permeability in vacuum. $A_n$ and $B_n$ is the complex amplitude of $H_y$ in each layer propagating along $-z$ and $+z$ direction, respectively. The field amplitude is associated by boundary conditions at the interface between adjacent layers. The tangential components of the electric and magnetic field are continuous at the interface, except that the magnetic field is not continuous at the 2DEG plane ($l_3 = 0$) due to the nonzero magnetoconductivity component $\sigma_{xx}$,

$$H_{y2}(\omega, k) |_{z=0} = H_{y4}(\omega, k) |_{z=0} = -\sigma_{xx} E_{z4}(\omega, k) |_{z=0}$$

(8)

The field amplitude for the incident wave was assigned firstly, and then field amplitudes of the zero-order propagating waves in the semi-infinite air (reflection part) and the substrate layer (transmission part) were determined according to the transfer matrix for the five-layer system [21]. Finally, the absorption spectrum was calculated as

$$\text{Absorption} = 1 - \left| \frac{A_{n=0}^{(4)}}{A_{n=0}^{(0)}} \right|^2 - \left| \frac{B_{n=0}^{(4)}}{B_{n=0}^{(0)}} \right|^2$$

(9)

where the second and third terms in the right equation are the corresponding power transmission and reflection coefficient.

Four typical heterostructure materials were studied and their parameters were listed in table 1, where the value of electron mobility ($\mu$) was given at room temperature. The grating period ($L$) was chosen differently to allow the first resonant peak to locate at around 1 GHz without magnetic field ($B = 0$) for the purpose of comparison. The grating filling factor ($W/L$) was set at 0.75 to have relatively strong scattered waves under the grating layer and to make sure the coupling between the THz field and 2D plasmons was strong enough at room temperature. Metal conductivity was $\sigma = 4.1 \times 10^7 \text{ S m}^{-1}$, and metal thickness was $t = 200 \text{ nm}$. In the experiment, the grating was realized by the technique of electron beam lithography.
3.1. Absorption spectra

Figure 2 compared absorption spectra of the four materials at room temperature with an external magnetic field of 1 T (figure 2(a)) and 10 T (figure 2(c)). The resonant frequency is determined by the real part of the complex frequency from the dispersion equation, and the peak width is associated to the imaginary part. The frequency, peak width and absorption amplitude depend on the plasmon wavevector (or the grating period) and the magnetic field.

At the low magnetic field $B = 1$ T, the electron cyclotron frequency $f_c$ is $0.13$ THz (GaN based materials), $0.44$ THz (AlGaAs/GaAs) and $0.15$ THz (SiGe/Si). Due to the low cyclotron frequency, the resonant peaks were mainly contributed by the 2D plasmon-polaritons according to the local approximation formula for the MPPs mode [22, 23]

$$\omega = \sqrt{\omega_c^2 + \omega_p^2}$$  \hspace{1cm} (10)

where $\omega_p = 2\pi f_p$ is the frequency of 2D plasmon-polaritons and $f_p \approx 1$ THz for the four materials at the wavevector of $k_1 = 2\pi/L$. At least four resonant peaks (denoted by down arrows $k_1 \to k_4$) corresponding to scattered wavevectors with different orders ($k_n = 2\pi n/L$) could be observed up to 5 THz for the AlGaN/GaN material due to its high electron concentration and mobility. The curves in figure 2(a) were similar to the case of plasmon-polaritons without magnetic field [12]. At cryogenic temperature ($77 \text{ K}$), the electron mobility increases and the resonance peak width becomes narrow. As shown in figure 2(b), besides the normal MPP resonances, the cyclotron resonances (CR) denoted by up arrows appeared in absorption spectra of AlGaN/GaN, AlGaAs/GaAs and SiGe/Si materials. In particular for the AlGaAs/GaAs material with the electron mobility of $5 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ at $77 \text{ K}$, high order CR harmonics (2nd, 3rd, and 4th CR) were discernable between different MPP resonances.

As the magnetic field increases to $10$ T, the cyclotron frequency is ten times the frequency at $B = 1$ T and well locates in the THz frequency range. As shown in figure 2(c) at room temperature, the first resonant peak position shifted to $1.53$ THz (AlGaN/GaN), $1.58$ THz (InAlN/GaN), $1.68$ THz (SiGe/Si) and $4.53$ THz (AlGaAs/GaAs).

In particular for the AlGaAs/GaAs material, its cyclotron frequency is $f_c = 4.4$ THz at $B = 10$ T and the observed resonance frequency at $k_1$ was introduced principally by the cyclotron frequency rather than the plasmon frequency according to equation (10). From the point of view of frequency tunability by the magnetic field, although the absorption amplitude was the minimum, the AlGaAs/GaAs material has the most wide frequency range ($\Delta_f \approx 3.55$ THz) due to its lowest electron effective mass. The observed frequency shift was almost three times the frequency shift obtained by traditional bias voltage on the grating coupler [12]. Moreover, the resonant peak was wide at room temperature and therefore the CR and high order CR harmonic resonances were smeared out in the MPP resonances. While at cryogenic temperature, the cyclotron resonance and its high order harmonics were distinguishable from the MPP resonances. It should be mentioned that at specific magnetic field and plasmon wavevector, the MPP modes will probably couple with Bernstein modes and the frequency splitting behavior will appear particularly at cryogenic temperature [14, 16]. Similar theoretical and experimental results for the AlGaN/GaN [24, 25] and CdMgTe/CdTe [15, 19] heterostructure materials have been reported.

The absorption amplitude decreases slightly with the magnetic field. The AlGaN/GaN material has the highest absorption due to its high electron concentration. It is the most sensitive material for THz detection at room temperature. Due to its lower electron mobility, the InAlN/GaN material has slightly smaller but comparable absorption as the AlGaN/GaN material. The AlGaAs/GaAs material suffers from its lowest electron concentration and the absorption amplitude is the minimum. The SiGe/Si material has the moderate performance in reference to both the absorption amplitude and the frequency tunability range.

3.2. Optimization of absorption spectra

The comparison between the four materials was based on the nominal parameters in table 1. The performance of each material could be further improved by changing its structural or material parameters. In this part, the influences of the grating period, filling factor and the barrier thickness on absorption spectra were evaluated for the two representative materials: AlGaN/GaN and AlGaAs/GaAs. Each time only one parameter was varied in the optimization process and other parameters remained unchanged.

3.2.1. Effects of the grating period

The grating period has direct impact on the plasmon wavevector by $k_n = 2\pi n/L$ and it will change both the amplitude and frequency in the absorption spectrum. As the increase of grating period, the plasmon wavevector decreases [12]. The period is usually chosen at several microns in order to make the resonant frequency locate in the THz range.

Figure 3 shows absorption spectra with the variation of grating period ($L$) from $0.5 \mu m$ to $5 \mu m$ for the two materials at $B = 10$ T. For the AlGaN/GaN material (figure 3(a)), the first MPPs resonance frequency
(absorption amplitude) shifted from 4.03 THz (0.16) at $L = 0.5 \mu m$ to 1.41 THz (0.23) at $L = 5 \mu m$. The fixed cyclotron resonance can be distinguished clearly if the grating period is equal to or below 1 $\mu m$, because the cyclotron frequency ($f_c = 1.27$ THz) is well separated with the MPPs resonance. For the grating period higher than $1 \mu m$, the broadened first MPP resonance makes the CR resonance smeared out. While for the AlGaAs/...
GaAs material in figure 3(b), the absorption frequency (amplitude) shifted from 4.62 THz (0.07) at $L = 0.5 \mu m$ to 4.5 THz (0.10) at $L = 5 \mu m$.

The absorption spectra at $B = 1 T$ have similar characteristics. Figure 4 shows the first MPP resonance frequency as a function of the grating period at room temperature. At $L = 0.5 \mu m$, the first MPP frequency is 3.8 (AlGaN/GaN), 2.7 (InAlN/GaN), 1.98 (AlGaAs/GaAs), and 2.33 (SiGe/Si) THz. As the grating period increases to 5 $\mu m$, the MPP frequency decreases to 0.43 (AlGaN/GaN), 0.47 (InAlN/GaN), 0.5 (AlGaAs/GaAs), and 0.29 (SiGe/Si) THz. In consideration of the frequency tunability at fixed magnetic field, the variation of grating period is an effective way to tune the MPPs mode frequency in a wide range.

It should be noted that if the grating period is fixed, the 2D plasmon will transfer from ungated to the gated case as the metal strip width ($W$) increases from 0 to $L$. The absorption peak will increase greatly because that the scattered field is strengthened as the filling factor increases and its interaction with 2D plasmon becomes intense. For the AlGaN/GaN material at room temperature with $B = 10 T$, the absorption amplitude increased from 0.17 at $W/L = 0.5$ to 0.25 at $W/L = 0.9$. The MPPs resonance was very weak at the case of low filling factor ($W/L = 0.25$). The minimum gap width was limited by the fabrication technology for the grating layer.

3.2.2. Effects of the barrier thickness
The barrier thickness has considerable effects on the absorption frequency and amplitude. With the increase of barrier thickness, the evanescent scattered wave and its interaction with the 2D plasmon becomes weak when it arrives at the 2DEG layer.

Figure 5 shows the influence of barrier thickness on absorption spectra for the two materials. In consideration of the fabrication technology, the maximum barrier thickness was chosen as 200 nm for the GaN based material and 100 nm for other materials. It can be observed that the resonant frequency increases with the barrier thickness in particular for the AlGaN/GaN material and the absorption amplitude decreases. For example, the first absorption amplitude (resonant frequency) shifted from 0.22 (1.45 THz) at $d = 10$ nm to 0.13
Figure 4. Comparison of the first MPP frequency for the four heterostructure materials as a function of the grating period ($L = 0.5:0.1:5 \, \mu m$) at room temperature with $B = 1 \, T$.

Figure 5. Absorption spectra in function of the barrier thickness ($d = 10–200 \, nm$ for AlGaN/GaN material and $d = 10–100 \, nm$ for AlGaAs/GaAs) at room temperature for AlGaN/GaN (a), and AlGaAs/GaAs (b) materials with $B = 10 \, T$. 
(2.43 THz) at $d = 200$ nm for the AlGaN/GaN material (figure 5(a)). The resonant frequency could be altered in a relatively wide range by the barrier thickness at the expense of decreased absorption amplitude (reduced detection sensitivity). While for the AlGaAs/GaAs material (figure 5(b)), the first absorption moved from 0.11 (4.47 THz) at $d = 10$ nm to 0.06 (4.52 THz) at $d = 100$ nm. For most heterostructure materials, the barrier thickness is tens of nanometers in order to have a strong scattered field at the 2DEG layer.

4. Conclusions

In conclusion, this work calculated and compared absorption spectra of four typical heterostructure materials (AlGaN/GaN, InAlN/GaN, AlGaAs/GaAs and SiGe/Si) for THz detection under the excitation of magnetic field. The nonlocal magnetocconductivity tensor was utilized for the modeling of electromagnetic properties of the 2DEG layer. The magnetoplasmon-polaritons (MPPs) resonances with wide peak width were observed in absorption spectra at room temperature. At cryogenic temperature, the cyclotron resonance (CR) and its high order harmonics probably appeared due to the narrowing of MPP resonances. According to the simulation results with the magnetic field from 1 to 10 T, the GaN-based material is most suitable for sensible THz detection at room temperature, while the resonant frequency could be tuned in a wide range for the AlGaAs/GaAs material. The absorption of the AlGaAs/GaAs material can be improved at cryogenic temperature. The SiGe/Si material has moderate performance from the aspect of absorption amplitude and frequency tunability.

By changing the grating period, filling factor and barrier thickness, absorption spectra in the AlGaN/GaN and AlGaAs/GaAs materials were optimized. The absorption amplitude was enhanced at a high grating filling factor and the resonance frequency of the AlGaN/GaN material was tuned effectively by the grating period.

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