A NON-BOLOMETRIC MODEL FOR A TUNABLE ANTENNA-COUPLED INTERSUBBAND TERAHERTZ (TACIT) DETECTOR

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Abstract

A number of Terahertz applications require detectors with time constants around 1 ns or less and with a certain minimum sensitivity. Detectors are still being developed to fill this niche in the few Terahertz frequency range. We propose a tunable antenna-coupled intersubband Terahertz (TACIT) detector that is expected to be more sensitive than available fast detectors.

When Terahertz radiation is incident on the device, a planar metal antenna couples the oscillating electric field from free space to the quantum well heterostructure, with the field polarization perpendicular to the plane of the quantum wells. Electrons in the active region of the channel quantum wells absorb the far-infrared radiation, exciting them from the ground to the first excited subband. The subbands are engineered to have different electron mobilities. As absorption alters the proportion of the electrons that are in the excited subband, the effective mobility of the device changes. A current is applied to the active area of the channel quantum well through source and drain contacts, and the change in effective mobility is detected as a change of the in-plane resistance of the device.

The device is sensitive to a narrow band of frequencies centered on the intersubband transition frequency. This center absorption frequency can be tuned by applying a bias voltage between the front and back gate contacts of the device.

The intrinsic speed of the TACIT detector is limited only by the excited subband lifetime, or intersubband relaxation time, which has been measured to be about 1 ns at a temperature of 10 K for several heterostructures with unbiased intersubband transitions near 3 THz.

The detector sensitivity can be estimated by calculating the change in population of the excited subband under illumination. In such a model, it is expected that a TACIT detector could be made to have 300K background limited performance (BLIP) while operating at 10 K. Such a device could be made with feasible device parameters. The theoretical model for the TACIT detector is presented.

1 Introduction

Intersubband transitions in quantum wells have enabled the development of sensitive quantum well infrared photoconductors (QWIPs) at frequencies greater than 15 THz. The potential of quantum well-based detectors in the range of 1-5 THz has not been realized For these frequencies, composite bolometers and Ga:Ge photoconductors are currently the most sensitive THz detectors for low-background astrophysical applications. The response times of these devices is 1 μs at best, typically much longer. Superconducting hot-electron bolometers are less sensitive but may have time constants of order 10 ps. For astrophysical applications, superconducting HEBs are used as mixers with noise temperatures an order of magnitude above the quantum limit for frequencies less than 2.5 THz. Both superconducting hot-electron bolometers and composite bolometers absorb radiation over a very broad band of frequencies.

We propose a tunable antenna-coupled intersubband Terahertz (TACIT) detector. Based on modeling presented in this paper and a previous paper[1], we expect it to be at least as sensitive as superconducting hot-electron bolometers and to have a response time variable from 1 ns to 10 ps by operating at different electron temperatures. The TACIT detector is narrowband, absorbing Terahertz radiation only in a small band of frequencies which can be tuned by applying small DC voltages

In the device section of the paper, an overview of the TACIT detector mechanism and structure will be presented. Intersubband absorption and two ideas for subband-dependent electron mobility will be discussed. In the following section, the calculation of the TACIT detector's expected performance will be outlined and the parameters in the model will be discussed. Calculations for predicted performance of a TACIT detector operating in a hot-electron bolometric mode are described elsewhere. [1] Work on making these devices has just recently begun, and will be discussed in a future paper.

2 Device

TACIT detectors can be patterned from a variety of quantum well heterostructures. Our samples are grown in the Molecular Beam Epitaxy (MBE) facilities at UCSB. The precise control of epitaxial layer growth possible through MBE allows clean interfaces between materials to be grown, and so gives the ability to truly tailor heterostructures. Quantum wells are used in the active region of TACIT detectors, such as the heterostructure shown in Fig. 1. Electrons in a quantum well are confined in the direction perpendicular to the plane of the well, and have quantized momenta in this direction. In the plane of the well, the electrons are free to move with any momentum. The combination of the discrete perpendicular-to-well confinement energy, and the in-plane kinetic energy gives rise to energy subbands within the quantum well. The TACIT detector heterostructure shown in Fig. 1 has a quantum well channel for the active region, and another quantum well for a back gate. The wells are filled by electrons from the silicon delta-doping layers. The doping levels and spacings are chosen such that the channel well only has electrons in the ground subband prior to illumination. The back gate quantum well is also designed such that electrons only occupy the ground subband.

When Terahertz radiation is coupled to the channel quantum well with the polarization of the electric field in the direction perpendicular to the plane of the well, electrons in the well can absorb the light, raising them from the ground subband to an excited subband. This intersubband absorption is a resonant process and can have a narrow linewidth, such as that shown in Fig. 2. In previous experiments, absorption peaks with a full-width-at-half-

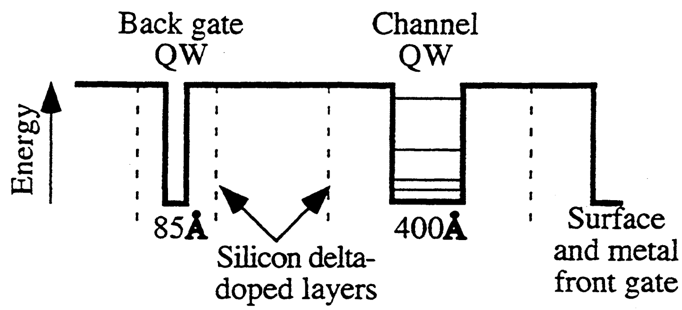

Figure 1: Schematic of one $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure being used for a prototype TACIT detector.

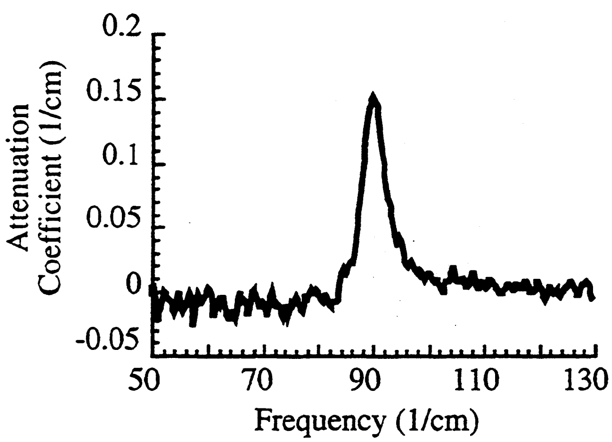

Figure 2: Attenuation measured as a function of frequency for the heterostructure shown in Fig. 1

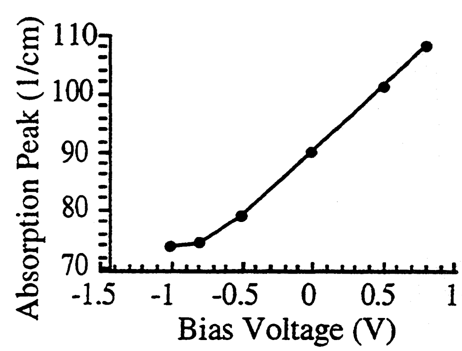

Figure 3: The frequency of peak absorption can be tuned by applying a bias voltage across the detector heterostructure.

maximum (FWHM) as small as 4 cm^{-1} = 120 GHz have been measured. There are many subbands in the channel quantum well, but only transitions between the ground subband and the first excited subband are considered here. The transitions to and among higher subbands are larger energy transitions, and so are not affected by light at the absorption frequency of the first two states.

A schematic of a TACIT detector is shown in Fig. 4. A planar metal broadband antenna couples the Terahertz radiation from free space to the active region of the detector, with the electric field polarized perpendicular to the plane of the quantum wells. Electrons in the channel quantum well absorb the radiation, which changes the percentage of electrons in each subband, which in turn changes the resistance of the active area. A current is sourced through metal ohmic source and drain contacts, and the change in resistance is measured as a change in voltage across the device. The two antenna leaves also serve as a front and a back gate, which are used to apply a DC voltage bias across the active region. The front antenna leaf makes a Schottky contact for the front gate, and the back antenna leaf is connected to the back gate quantum well through an ohmic contact.

A DC voltage bias is applied across the channel quantum well in order to change the

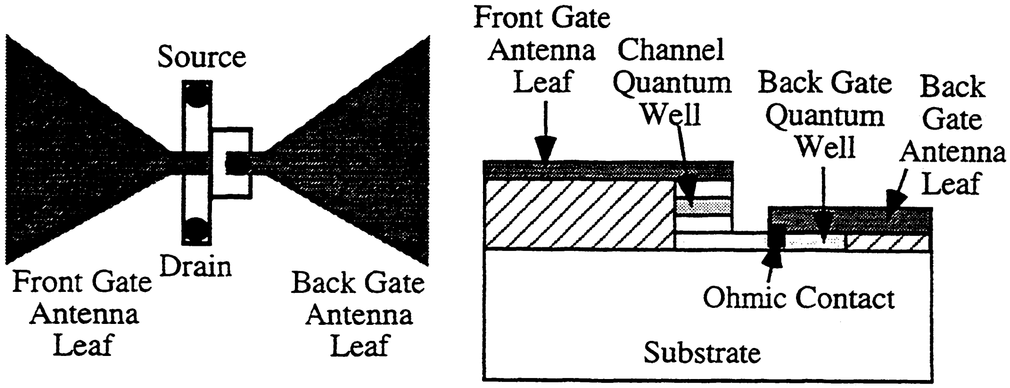

Figure 4: Top-down and cross-section views of a TACIT detector. Ohmic contacts electrically connect the back gate antenna leaf with the back gate quantum well, and the source and drain contacts to the channel quantum well. The active region of the device is defined by making the material outside, indicated by diagonal lines, electrically insulating.

subband energy spacing, and thereby tune the frequency of peak absorption. By applying moderate voltages, the resonant absorption frequency can be tuned over a range that is a significant portion of the original frequency, as shown in Fig. 3 for a typical TACIT heterostructure. Tuning the absorption frequency is simple and can be done while the detector is operating. TACIT detectors could then be used for a wide array of applications, including, in certain situations, to record spectra without the use of a bulky spectrometer. Additionally, the electron density in the channel quantum well can be tuned by applying a DC voltage to the source and drain contacts to the channel. This flexibility allows for fine-tuning the impedance of the device to match the antenna. Independent control of the front gate, back gate, and channel DC voltages allow simultaneous tuning of the intersubband absorption frequency and electron sheet density.

The channel quantum well subbands are engineered to have different electron mobilities, so as absorption alters the proportion of the electrons that are in the excited subband, the effective mobility of the device changes. Many different mechanisms could be used to give the two subbands different mobilities. Two that are currently being pursued are to use the electrons' wavefunctions in the quantum well to alter their scattering profiles, and to use a low enough electron sheet density such that the electrons in the ground subband are localized. In both cases, the current effort involves making the ground subband mobility, μ_0 less than the excited state mobility, μ_1. In the absence of illumination, all the electrons are in the ground subband, and the device has a high resistance. If the subband mobility ratio, μ_1/μ_0, is large, then when electrons are promoted to the excited subband, they can effectively short out transport in the lower subband. The device would thus have a sharply dropping resistance when just a small fraction of the channel electrons are raised to the excited subband. It is also possible to make the ground subband mobility higher than the excited subband mobility ($\mu_1/\mu_0 < 1$), but the resulting changes in resistance would be harder to measure.

The first mechanism for differentiating the subband mobilities takes advantage of the different spatial probability amplitudes of the two subband wavefunctions. For the heterostructure shown in Fig. 1, a spike of electrically-compensated impurities is grown in the center of the channel quantum well. Ionized impurities are used to give a larger scattering cross section than neutral ions, and two types of dopants are used so that the resultant spike is electrically neutral, and should not change the quantum well potential. The ground subband is symmetric in the well, and has its maximum in the center of well, where the impurity spike is, so the electrons in the ground subband should scatter strongly from the impurities. The first excited subband wavefunction is antisymmetric in the well, and has a node in the center of the well. The electrons in the excited subband should spend most of their time away from the impurity spike, and so should scatter far less and have a much higher mobility than the electrons in the ground subband. This mechanism has been studied analytically by Hai and Studart.[2]

The second mechanism for differentiating the subband mobilities is a transition from localized electron states to non-localized states. The electron sheet density in the channel quantum well can be made low enough, a few times $1 \times 10^{10}\text{cm}^{-2}$, so that the ground subband is comprised of localized electron states, but the first excited subband has non-localized electron states. Conduction in the ground subband would be through hopping from one localized puddle to the next, and could be made very low by decreasing the electron density or lowering the temperature. When electrons absorb Terahertz light and are excited to the first excited subband, these electrons would be promoted to non-localized states, and could conduct without hopping. In this manner, the first excited subband would have a much larger mobility than the ground subband. The mobility of electrons undergoing a transition from an insulating state to a metallic state has been measured by Finkelstein et al[3] for quantum well structures similar to those being used for TACIT detectors.

In the calculations of the expected TACIT detector performance, both the impurity spike and localization mechanisms are considered together. The value used for the subband mobility ratio, μ_1/μ_0, is taken from the data presented by Finkelstein et al.

3 Expected Figures of Merit

The relevant characteristics of an incoherent detector are the sensitivity, speed, and frequency response. These characteristics can be expressed in terms of the noise equivalent power (NEP), response time, and the corner frequency f_c respectively. We assume that the electrons in the ground subband can be described by a thermal distribution with an electron temperature, T_e. The detector will generally be operated at a low bias power so all the electrons are assumed to be in the ground state in the absence of illumination. The system is also assumed to have a single energy relaxation time, T_1. We consider coupling the incident light to the antenna and coupling from the antenna to the device. We do not, however, include effects associated with coupling the detector to an outside sample mount or electronic circuit, such as heat diffusion or amplifier noise.

The noise equivalent power, NEP, is the root mean square amplitude of sinusoidally modulated radiation power incident on the detector required to produce a unity signal to noise ratio ($S/N = 1$) in a 1 Hz bandwidth. The NEP can be expressed as the ratio of the rms noise voltage, V_n (in V/Hz^{-1}), to the responsivity, $\mathcal{R}$ (in V/W). The responsivity, $\mathcal{R}$, is the change in output voltage per unit incident power. A constant current is sourced to the device, and the change in voltage comes from variations in the source-drain resistance, R_{SD}.

$$\mathcal{R} = \frac{dV}{dP_{inc}} = \eta_{FA}\eta_{AD}I_{SD}\frac{dR_{SD}}{dP_{abs}} \tag{1}$$

η_{FA} is the coupling efficiency from free space to the antenna, and η_{AD} is the coupling efficiency from the antenna to the active area of the device. I_{SD} and R_{SD} are the applied source-drain current and source-drain resistance respectively. P_{abs} is the signal power that is absorbed in the detector active region.

The device resistance changes as electrons absorb the Terahertz radiation, raising them from the ground subband to the excited subband. In the absence of inter-valley scattering, conduction in the two subbands can be considered to occur independently and in parallel. [4] The effective resistance of the active area is then the resistances of the two subbands added in parallel. Resistance is inversely proportional to mobility, so an effective mobility can be defined,

$$\mu_{eff} \equiv \frac{N_0}{N_{Total}}\mu_0 + \frac{N_1}{N_{Total}}\mu_1 \tag{2}$$

where N_0 and N_1 are the number of electrons in the ground and excited subbands, and $N_{Total} = N_0 + N_1$. The total number of electrons in the channel quantum well does not change in operation, but how many are in each subband does. The differentiation in the responsivity expression, Eq. 1 can be carried through to variations in the effective mobility with incident light.

$$\begin{aligned}\mathcal{R} &= \eta_{FA}\eta_{AD}I_{SD}\mathcal{G}_{SD}\frac{d\rho_{eff}}{dP_{abs}} \\ &= \eta_{FA}\eta_{AD}I_{SD}\mathcal{G}_{SD}\frac{1}{eN_{\text{Total}}}\frac{d(1/\mu_{eff})}{dP_{abs}} \\ &= \eta_{FA}\eta_{AD}I_{SD}R_{SD}\left(\frac{-1}{\mu_{eff}}\frac{d\mu_{eff}}{dP_{abs}}\right) \end{aligned} \tag{3}$$

with $\mathcal{G}_{SD}$ being a geometric factor of the dimensions of the source-drain region.

A photon has a certain probability of being absorbed by an electron in the ground subband. With a sufficiently low incident power, the number of electrons will be much larger than the number of photons arriving in the intersubband relaxation time. Assuming all electrons are initially in the ground subband, the number of electrons in the excited state will then be simply the number of photons at the resonance frequency, f_0, arriving in the detector within the intersubband relaxation time, T_1.

$$N_1 = \frac{P_{abs}T_1}{hf_0}$$

An electron in the excited subband has several ways of relaxing back to the ground subband. The excited electron can spontaneously emit a photon, or it can undergo stimulated emission. We assume, however, the detector will be looking at weak signals, so the photon density will be small, and the rate of stimulated emission will be negligible compared to other relaxation mechanisms. An excited electron can also release energy and momentum by emitting a phonon. If the electron has sufficient energy to emit a longitudinal-optical (LO) phonon, 36 meV in GaAs, it will rapidly do so, for LO phonons are strongly coupled to the electrons. A few picoseconds is a typical relaxation time constant for LO phonon emission in GaAs/AlGaAs quantum well heterostructures. If the excited electron does not have enough energy to emit a longitudinal-optical phonon, it can still emit an acoustical phonon. These acoustical phonons have no minimum energy, and are less strongly coupled to the electrons than LO phonons. For greatest sensitivity, the TACIT detector is operated such that the electrons excited to the upper subband cannot emit a LO phonon, and so have a longer lifetime in the excited state. The intersubband relaxation time constant has been measured for samples similar to the heterostructures being used for prototype TACIT detectors.[5] The time constant $T_1 = 1ns$ for an electron temperature $T_e = 10\ K$, where the electrons effectively cannot emit LO phonons. For an electron temperature $T_e = 50\ K$, $T_1 < 10\ ps$. At $T_e = 50\ K$, the electrons still have an average energy far below the LO phonon energy, but the tail of the electrons' Fermi energy distribution is large enough that a small fraction of the excited electrons can emit an LO phonon. Energy relaxation by emission of a LO phonon is significantly faster than by acoustic phonons, so that even with only a small fraction of electrons with sufficient energy, emission of LO phonons becomes the dominant energy relaxation mechanism. The intersubband relaxation time, T_1, includes all these mechanisms.

As the total number of electrons in the channel quantum well is constant and $N_{Total} = N_0 + N_1$, the population change of the excited subband is simply negative that of the population change of the ground subband,

$$\begin{aligned} \frac{d\mu_{eff}}{dP_{abs}} &= \frac{1}{N_{Total}}\left(\mu_0\frac{dN_0}{dP_{abs}} + \mu_1\frac{dN_1}{dP_{abs}}\right) \\ &= \frac{1}{N_s A_{SD}}\left(\mu_0\frac{-T_1}{hf_0} + \mu_1\frac{T_1}{hf_0}\right) \\ &= \frac{T_1(\mu_1 - \mu_0)}{hf_0 N_s A_{SD}} \end{aligned} \tag{4}$$

The responsivity is proportional to the change in effective mobility with varying signal power, which is in turn proportional to the changes in the relative subband populations. Combining Eqs. 3 and 4, the responsivity for low signal powers can be expressed,

$$\mathcal{R} = -\eta_{FA}\eta_{AD}I_{SD}R_{SD}\frac{(\mu_1 - \mu_0)}{\mu_0}\frac{T_1}{hf_0 N_s A_{SD}} \tag{5}$$

The responsivity is proportional to the ratio of the difference between subband mobilities to the ground subband mobility. It is also inversely proportional to the active region area and resonance frequency.

This expression of the responsivity also includes the two antenna coupling factors, η_{FA} from free space to the antenna, and η_{AD} from the antenna to the active region of the device. Using a transmission line model, η_{AD} is the fraction of of the power delivered through the transmission line to the active region of the device. On resonance, with $f = f_o$, the detector active region can be modeled as a resistance in parallel with a parasitic capacitance. This resistance is not the source-drain resistance of the device, but rather is the resistance sensed by the radiation-induced Terahertz voltages between the front and back antenna leaves.

$$R_{\perp} = \frac{d}{A_{SD}\sigma_{3-D}} = \frac{2\pi c\; m^* d^2 \text{FWHM}}{e^2 A_{SD} N_S f_{osc}}$$

where d is the distance between the gates and the channel quantum well and A_{SD} is the area of the active region. FWHM is the full width at half maximum of the intersubband absorption peak (in cm^{-1}), m^* is the conduction band effective mass of the electrons, N_S is the sheet density of electrons in the channel well, and f_{osc} the oscillator strength of the transition between the ground and first excited subbands. This expression is for a low signal power regime, where there are no saturation effects. When this resistance 'perpendicular' to the plane of the quantum wells is matched to the antenna impedance, $R_{ant} = 71\Omega$ for our log-periodic antenna, η_{AD} simplifies to,

$$\eta_{AD} = \frac{1}{1 + (f/f_c)^2}$$

with a corner frequency,

$$f_c = \frac{1}{\pi R_{\perp} C} = \frac{e^2}{2\pi^2 c m^* \epsilon} \frac{N_S f_{osc}}{d\text{FWHM}}$$

The corner frequency, along with the intersubband absorption lineshape and tunable resonance frequency, specify the spectral characteristics of a TACIT detector.

Having now an expression for the responsivity, the expected noise equivalent power for a TACIT detector can be computed. Considering Johnson noise, generation-recombination noise, and fluctuations in the thermal background, the detector's NEP can be written,

$$\text{NEP}^2 = \frac{4K_B T_e R_{SD}}{\mathcal{R}^2} + \frac{4eI_{SD}R_{SD}^2}{1 + (2\pi f T_1)\mathcal{R}^2} + \left(\frac{hfc\,\text{FWHM}}{\exp\left[\frac{hf}{K_B T_{Bkgnd}}\right] - 1} \right)^2 \frac{1}{c\,\text{FWHM}} \qquad (6)$$

To estimate the performance possible for a TACIT detector using the subband-dependent mobility mechanism, device parameters were taken from the heterostructure design, device processing considerations, and, where applicable, from related experiments. Several factors constrain the choice of parameters. The primary constraints are to match the impedance of the detector active region to that of the antenna, and to consider signal and bias Joule-heating powers to yield an electron temperature that is consistent with the desired subband relaxation time constant. The first constraint relates the active area A_{SD}, gate to channel distance d, and the sheet density of electrons in the channel quantum well N_S. The corner frequency also involves the separation d and electron sheet density, and this frequency should ideally be much larger than the operation frequencies of interest. The responsivity is inversely proportional to the device active area, A_{SD}, as shown in Eq. 5, so to get the highest sensitivity, minimizing the area must be balanced against the corner frequency and impedance-matching criteria. The second constraint limits the total power that can be considered for a given intersubband relaxation time constant, T_1. The total power absorbed, both signal power and bias Joule heating power, $I_{SD}^2 R_{SD}$, absorbed within the relaxation time will heat the electrons above the semiconductor lattice temperature, T_L,

$$\left(P_{Signal} + I_{SD}{}^2 R_{SD}\right) T_1 = C_v(T_e)(T_e - T_L)$$

Sourced current I_{SD}	0.1μA	Area A	$2\mu m^2$
Source-drain resistance R_{SD}	1 kΩ	Gate separation d	$0.17\mu m$
Resistive impedance $R_\perp$	70 Ω	Absorption FWHM	4 cm^{-1}
Intersubband relaxation T_1	1 ns	Electron temp. T_e	12K
Electron sheet density	$4 \times 10^{10}cm^{-2}$	Lattice temperature T_L	10K
Free space-antenna coupling η_{FA}	0.5	Oscillator strength f_{OSC}	0.9
Subband mobility ratio μ_1/μ_0	300		

Table 1: Parameters used in calculating TACIT detector operating characteristics.

Parameter	f = 1.0 THz	f = 1.8 THz	f = 5.0 THz
Responsivity [V/W]	-2.6×10^7	-1.2×10^7	1.9×10^6
NEP, 300 K bkgnd $[W/Hz^{1/2}]$	$\mathbf{1.3 \times 10^{-15}}$	$\mathbf{1.2 \times 10^{-15}}$	$\mathbf{1.0 \times 10^{-15}}$
NEP, 77 K bkgnd $[W/Hz^{1/2}]$	$\mathbf{2.7 \times 10^{-16}}$	$\mathbf{2.1 \times 10^{-16}}$	4.4×10^{-16}
NEP, 10 K bkgnd $[W/Hz^{1/2}]$	3.1×10^{-17}	6.6×10^{-17}	4.4×10^{-16}

Table 2: Expected responsivities and noise equivalent powers for a TACIT detector operating at 1.0 THz, 1.8 THz, and 5.0 THZ, with thermal background noise from a 300 K, 77 K, and 10 K blackbody source. Entries in bold type indicate background-limited sensitivity.

where $C_v(T_e)$ is the specific heat of the electrons. The resulting electron temperature must be consistent with the relaxation time used to calculate it.

The parameters used to estimate the performance of a TACIT detector are given in Table 1. The parameters are design characteristics, with the ratio of subband mobilities, μ_1/μ_0, and the coupling constant η_{FA} taken from the literature.[3, 6]. These parameters are all feasible to achieve. The responsivities and noise equivalent powers for such a TACIT detector under various conditions is summarized in Table 2. With these experimentally-feasible parameters, a TACIT detector operating at its resonant absorption frequency of 1.8 THz is expected to have 77 K-background-limited sensitivity and 300 K-limited performance for frequencies to and beyond 5 THz with a intersubband relaxation time constant of 1 ns.

4 Summary

Intersubband transitions in quantum wells are a unique system for making detectors for the 1-5 THz frequency range. TACIT detectors are narrowband, with an absorption peak linewidth FWHM = $4cm^{-1}$ = 120GHz measured for similar heterostructures, and are tunable by applying a moderate bias voltage. Using quantum well heterostructures designed to give a large subband mobility ratio, absorbing a low signal power is expected to dramatically change the effective mobility of the device active region. This change in mobility is measured as a change in source-drain resistance of the detector. A parallel-current-path model is used to calculate the expected performance of the TACIT detectors. With a set of experimentally-feasible device parameters, TACIT detectors are expected to have background-limited sensitivity for a 300 K background, and for some frequencies, even for a 77 K background. The intrinsic speed of TACIT detectors is predicted to be limited only by the intersubband relaxation time, which is variable, and is in the range of 1 ns to less than 10 ps. This expected performance compares favorably to other detector technologies.

Acknowledgments

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