Tunable Antenna-Coupled Intersubband Terahertz (TACIT) Detectors for Operation Above 4K

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Abstract

The necessity of liquid helium for detectors and sources makes THz space and balloon missions heavy, bulky, and expensive. Tunable Antenna-Coupled Intersubband Terahertz (TACIT) detectors are predicted to operate at temperatures above 4K with good sensitivity. Modeling predicts that TACIT detectors could be operated as direct detectors at 20K with 300K background-limited sensitivity. This flexibility in operating temperature comes from the semiconductor quantum well heterostructures that are used in the detectors. Semiconductor materials and processes also give TACIT detectors flexibility in absorption frequency, time constant and other operating parameters. With this flexibility, it is predicted that TACIT detectors could be made fast enough to operate as sensitive mixers with multi-Gigahertz bandwidths.

A process for making TACIT detectors has been developed. A brief description of TACIT detector fabrication and operation is presented. Flexibility in TACIT detector operating parameters is discussed.

1 Introduction

Astronomical observing from space requires sensitive detectors, which with current technology must be cooled with liquid helium. Liquid cryogens add to the weight and size of satellites, and so add significantly to the overall mission cost. Liquid cryogens also add to the complexity of operating satellites and can limit mission duration. For all of these reasons, detectors are desirable that are sensitive while operating without liquid cryogens. These detectors would also be useful in a broader array of applications since they wold be more sensitive than current high-temperature detectors such as Schottky diodes.

Low-power mechanical coolers such as hydrogen sorption coolers can offer milliwatt cooling powers at 20K. Current state-of-the-art detectors for space missions are low-temperature composite bolometers and low-T_c superconducting devices. Composite bolometers rely on low temperatures for a large signal to noise ratio. Low T_c superconductors would be fully in the normal state above 20K, and so would also not be useful. Semiconductor devices, however, including Schottky diodes and FET amplifiers, can operate above 20K. Semiconductor materials also offer great flexibility in designing devices, such that it is possible to design sensitive detectors to operate at these warmer temperatures.

This paper presents how Tunable Antenna-Coupled Intersubband Terahertz (TACIT) Detectors can be operated above 20K with high sensitivity. First the structure and fabrication procedure for a TACIT detector will be discussed. Next the detection mechanism will be described. Then, using a model presented in a previous paper,[1] predictions for operation characteristics will be presented. Lastly, the flexibility of TACIT detectors to be tailored for different applications will be discussed.

2 Device

TACIT detectors are made from semiconductor quantum well heterostructures. Current TACIT designs are based on a GaAs/$Al_{0.3}Ga_{0.7}As$ structure with two quantum wells, shown in Fig. 1. One quantum well is for the active channel region, and the other is designed to connect to the back gate antenna leaf. Electrons are supplied to each quantum well by silicon doping layers outside the wells. The channel quantum well is 400Åwide, which sets the tunable range of the detector. The device consists of a two-level mesa surrounded by GaAs where the quantum wells have been etched away, as shown in Fig. 2. The lower mesa level gives electrical access to the back gate quantum well. The device has four electrical terminals, front and back gates and a source and drain.

Current TACIT detectors are fabricated from the semiconductor heterostructure wafer in five processing steps. The first two steps are chlorine-based reactive ion etches to form the two-tiered mesa structure. Then layers of Ge, Au, and Ni are evaporated onto the sample and annealed to form the ohmic contacts. Next, Ti and Au are evaporated onto the sample to form the antenna. Lastly more Ti and Au are evaporated to create thick metal contacts for wire bonding. The detectors are then cleaved apart, and each one is mounted in a copper sample holder for testing.

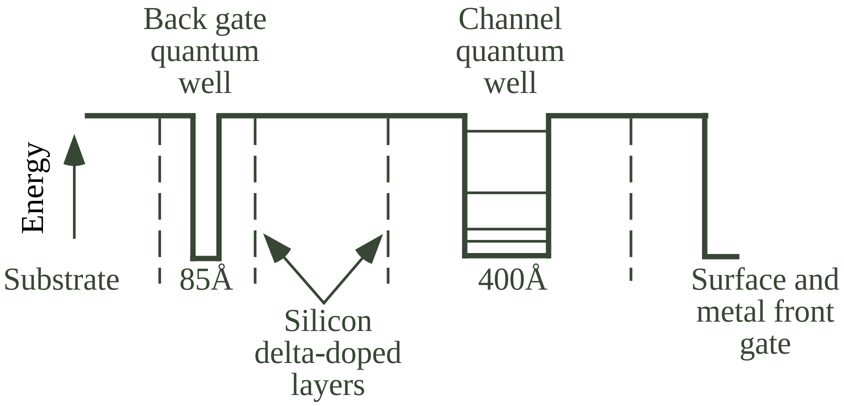

Figure 1: Schematic of one GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure being used for a prototype TACIT detector.

3 Operation

The basic operation principle of TACIT detectors is that THz light is absorbed in an intersubband transition by electrons in the channel quantum well. with the result that the in-plane resistance of the device changes. There are many mechanisms that can be used to cause the change in resistance. This paper will discuss only one of these mechanisms, but two other mechanisms, one bolometric and the other impurity scattering, have been presented in previous papers.[2, 3]

THz electric fields are concentrated and coupled into the detector with a planar metal antenna. The TACIT detector has four electrical terminals for which signals must be brought to or from the active region. The THz fields are coupled to the front and back gate by a log-periodic toothed antenna. DC voltages are also applied to the antenna leaves via inductive meander lines which block the THz currents. The source and drain are connected to larger contact pads away from the active region by straight wires. This combination is less than ideal, since the straight metal lines can act as a dipole antenna and can also capacitively short the log-periodic antenna. Since there are no published four-terminal antenna designs that are purely planar, for future devices we will use designs that will have a layer of dielectric and a second metal layer to allow the metal leads from the source and drain to cross over the metal of the antenna.

The antenna serves a second important function. The leaves of the antenna are used to change the polarization of the THz electric fields so that they can be absorbed by the electrons in the quantum well in an intersubband transition. Linearly polarized light hitting the antenna at normal incidence induces currents in the antenna leaves. The front gate antenna leaf goes up the side to the top of the mesa.

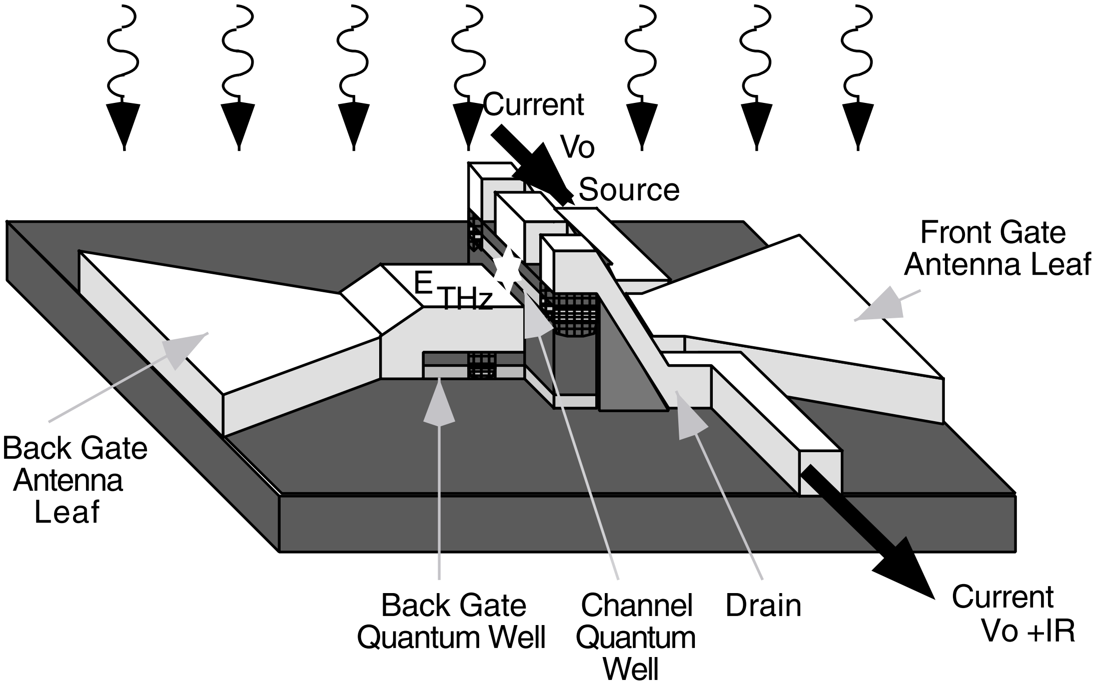

Figure 2: Schematic view of a TACIT detector. Ohmic contacts electrically connect the back gate antenna leaf with the back gate quantum well, and the source and drain contacts to the channel quantum well.

The back gate antenna leaf is electrically connected to the back gate quantum well by an ohmic contact, allowing the oscillating currents to flow from the antenna leaf through the back gate quantum well to the material under the active region. Thus, the THz oscillating electric fields in the active region of the detector are polarized in the direction perpendicular to the quantum well (polarized in the growth direction.) This allows the electrons in the quantum well to absorb the THz radiation in an intersubband transition, which is forbidden for THz fields in the plane of the quantum well. In most previous THz quantum well detectors, the THz oscillating fields were in the plane of the quantum well, and coupled to the electrons via other mechanisms, such as in-plane electron heating. Intersubband transitions are resonant transitions and so yield much stronger coupling between electrons and THz light.

For TACIT detectors, absorbing THz light yields a change in the in-plane electrical resistance of the device. Current TACIT detectors accomplish this by nearly depleting the electrons out of the channel quantum well such that those remaining are trapped in potential fluctuations. The electrons, localized in puddles, can only carry current by hopping conduction, yielding a high effective resistance. Electrons absorbing THz radiation can go to higher energy states that are not localized and thus can carry current with a much lower effective resistance. By analogy with the metal-insulator

Noise equivalent power	8x10^{-16}W/Hz$^{1/2}$
Time constant	33ps
Operating (lattice) temperature	20K
THz frequency (tunable)	2.4-4.5 THz
Size of active area	4μm^2
Vertical separation of gates	3430Å
Charge density	8x10^{10}cm^{-1}
Oscillator strength	0.9
Source-drain voltage	2mV
Source-drain resistance	1kΩ
Mobility ratio	100

Table 1: Model parameters for a TACIT detector operating characteristics.

transition for electrons in a quantum well, we expect to be able to achieve a ratio of effective electron mobilities of around 100.[4] Following modeling presented previously (see Eq. 6 in Ref.[1]), this electron mobility ratio yields a detector that is predicted to have background-limited sensitivity with feasible device parameters, as shown in Table 1.

TACIT detectors have a flexible design allowing them to be optimized toward different operating characteristics. Since the THz (RF) and source/drain (IF) signals travel in different directions, the electrical circuits for each frequency can be designed independently. Additionally, having both a front gate and a back gate allows the charge density and absorption frequency to be independently tuned. By applying a DC voltage on both gates with respect to the channel quantum well, the density of electrons in the channel can be varied. This allows the mobility contrast mechanism mentioned above to be implemented, or could allow the RF impedance of the device to be tuned to precisely match the antenna impedance. By applying differing DC voltages to the gates, an electric field is created across the quantum well, which tunes the intersubband absorption frequency, as shown in Fig. 4.

The time constant of TACIT detectors can also be tailored to fit applications. The time constant can be in the range of a few ps to 1 ns. Longitudinal optical (LO) phonons couple strongly with electrons, making energy relaxation via LO phonons a fast process, taking around 1ps. However, the minimum energy of an LO phonon in GaAs is 36meV (corresponding to a temperature of 420K). Since the energy spacing between the lowest subbands is much smaller, cold electrons in these subbands can only emit acoustical phonons. Purely acoustic phonon cooling at a 10K electron temperature yields a time constant of 1ns.[5] However, if the electron temperature is raised to 50K, the time constant is lowered to below 10ps. The energy of the

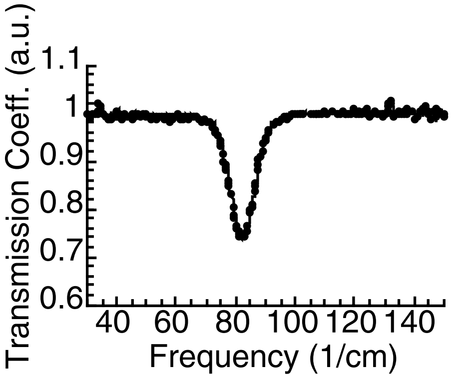

Figure 3: Attenuated transmission measured as a function of frequency for a piece of the heterostructure wafer drawn in Fig. 1.

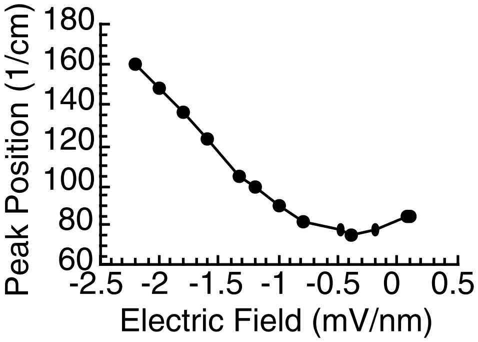

Figure 4: The frequency of peak absorption can be tuned by applying a bias voltage across the detector heterostructure.

majority of electrons is still too low to emit an LO phonon, but a few electrons in the high energy end of the Fermi distribution can, which significantly lowers the time constant of the whole electron gas. Another cooling mechanism that can take part in small semiconductor devices is diffusion of the hot electrons out of the active region. Diffusion cooling has been used in many submicron-sized superconducting hot electron devices. However, the electron mobility of modulation-doped semiconductor quantum wells is orders of magnitude larger than for superconductors, so diffusion cooling in semiconductor devices can dominate for devices that are as long as a few microns. Thus diffusion will add to phonon cooling for many semiconductor devices. The physical dimensions and operating temperatures of TACIT detectors can be chosen to optimize the time constant for a particular application. The time constants can be chosen to be small enough that TACIT detectors could be used as mixers with several GHz predicted intermediate frequency (IF) bandwidth.

The potential barrier walls of quantum wells are sufficiently deep to allow semiconductor-based TACIT detectors to be operated at temperatures of tens of Kelvin. Electrons are still well confined in the quantum well at electron temperatures around 50K. Quantum well heterostructures can be tailored to have strong or weak confinement, as needed, by adjusting the materials used to form the wells. Thus TACIT detectors do not inherently lose all their sensitivity at elevated electron temperatures as low-T_c superconductors do. Material selection and device patterning can also allow control over thermal properties of electrical transport.

4 Project Status and Future Work

TACIT detectors have been processed in the UCSB cleanroom facilities. Work is underway to simplify the device design and make a new batch of detectors designed to allow easier study of the detection mechanisms. First, a device structure will be implemented that does not have an antenna, so that operating characteristics will all be due to the detector, and not to a non-optimal four-terminal antenna design. The THz electric fields will be made perpendicular to the plane of the quantum wells by reflecting a free-space propagating, linearly-polarized THZ beam off the device through a silicon prism or lens. In the vicinity of the metal front gate, the electric field is constrained to be perpendicular to the gate, and so will be perpendicular to the quantum wells. Direct absorption measurements will be made. Also planned are more and better diagnostic structures, such as contacts for Van der Pauw resistivity measurements, which will be incorporated in or near the detector structure. With these changes the behavior of the TACIT detector can be studied more directly.

Once the TACIT detection mechanisms are verified and more closely studied, then work can proceed on improving and optimizing TACIT detectors for use as direct detectors or for use in THz mixers. Work could also begin on a next-generation TACIT detector that uses two additional voltage-controlled gates to control the in-plane electrical transport. Modeling predicts that mixers incorporating these advanced-design TACIT detectors could achieve quantum-limited sensitivity while operating at a bath temperature of 20K.

Acknowledgments

This work has been supported by the NSF Science and Technology Center for Quantized Electronic Structures (QUEST) DMR 91-20007, NSF DMR 9623874, AFOSR91-0214, and the NPSC (CC).

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