Ultrafast Tunable Antenna-Coupled Quantum-Well THz Detectors Operating Above 100K

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Abstract

This extended abstract reports on the fabrication and testing of a new type of detector in which THz radiation excites a collective oscillation of electrons confined in a quantum well and set between two gates in a microscopic four terminal transistor. The energy dissipates into other modes of the electron gas, warming it and changing the source-drain resistance. The detector shows amplifier-limited rise times near 1 ns and has detected THz laser radiation at temperatures up to 120K. The frequency of the collective oscillation tunes with small gate voltages. The first-generation tunable antenna-coupled intersubband Terahertz (TACIT) detectors tune between 1.5 and 2 THz with voltages <2V.

Introduction

The development of detectors for THz radiation has been largely driven by the astrophysics community. The result is a set of detectors with exquisitely low noise which require cooling to temperatures below 4K. These detectors will not find their way into wide commercial application because of the prohibitive cost, mass and complexity of deep cryogenics.

We have previously proposed and analyzed theoretically a new type of detector, the tunable antenna-coupled intersubband terahertz (TACIT) detector.[1,2] TACIT detectors promise low noise, speed sufficient to be useful as fast detectors or as mixers with large intermediate frequency (IF) bandwidths, tunability with a small applied dc voltage, and operation at temperatures well above 4K. In this abstract we present results on the fabrication and performance of the first generation of TACIT detectors.

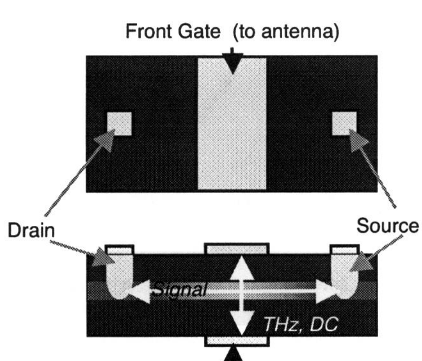

Fig. 1: Schematic diagram of the active region of a TACIT detector from top (upper) and side (bottom).

Principles of operation

A schematic diagram of the active region of a TACIT detector is shown in Fig. 1. The active region consists of a ~4.5µm x 4.5 µm x 0.7 µm volume which contains an electron gas confined to a pair of coupled quantum wells. The top and bottom of the active region are defined by a front gate and a back gate. These gates are coupled both to an antenna for THz radiation (Fig. 2) and to dc voltages that allow a static electric field to be applied parallel to the growth direction. The intersubband plasmon[3] is a collective mode of the electrons. In coupled quantum wells, this mode corresponds to the electrons sloshing back and forth as they tunnel in phase through the barrier separating the two wells. The frequency of the intersubband plasmon is tunable with an applied dc electric field.[4] When THz radiation resonant with this intersubband plasmon is absorbed in the active region, it quickly dissipates into other modes of the electron gas, warming it up. Warming the electrons increases the scattering rate for in-plane transport, increasing the resistance for currents traveling in the plane of the quantum wells (perpendicular to the growth direction). A source and drain are used to sense the change in resistance caused by absorption of THz radiation in the active region.

TACIT detector fabrication

The following epitaxial structure was grown by molecular beam epitaxy (MBE): starting at the surface, a 10nm GaAs cap layer, 130nm $Al_{0.3}Ga_{0.7}As$, 1 monolayer Si delta doping, 70nm $Al_{0.7}Ga_{0.3}As$, a 10.8nm GaAs well, a 3nm $Al_{0.3}Ga_{0.7}As$ barrier, a 9nm GaAs well, 70 nm $Al_{0.3}Ga_{0.7}As$, 1 monolayer Si delta doping, 197nm $Al_{0.7}Ga_{0.3}As$, 200nm GaAs and a 1 micron $Al_{0.7}Ga_{0.3}As$ etch stop layer.

Devices were fabricated using step-and-repeat photolithography. The process was based on the epoxy-bond and stop-etch (EBASE) technique[5]: First two Au/Ge/Ni/Au 100 x 100 µm ohmic contact pads were defined, metallized and annealed, separated by 5µm, for the source and drain. Next, a twin-slot antenna[6] (black H-shape in Fig. 2), co-planar waveguides (cpw), filters and Schottky gates were deposited in one Ti/Au metallization step. The wafer was subsequently glued processed side down on a host GaAs wafer. In this way it was possible to chemically remove the 0.5 mm thick substrate of the processed wafer with one selective etch stopping at the $Al_{0.7}Ga_{0.3}As$ etch stop layer, and a second stopping at the subsequent GaAs layer. After etching off the back, a 700nm thick membrane remained, terminated with a GaAs layer and supported by the carrier wafer. To define the active region a 500nm tall dumb-bell shaped mesa was etched, 5µm wide at its narrowest point. A hole was etched through the remaining 200nm of AlGaAs to the center conductor of one of the cpw lines. This hole was filled by subsequent metallization and

electrically connected the top gate to the buried center conductor of one of the cpw lines. For measurement, the devices were diced into 2mm by 2mm chips and glued on a 12mm or 6mm diameter silicon lens.

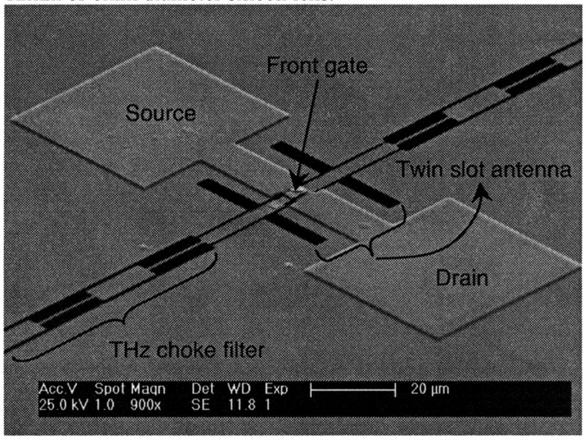

Fig. 2: Scanning electron micrograph of TACIT detector. Metallization (light gray) is seen through 200 nm of AlGaAs insulator. Dark regions are not metallized.

Performance

TACIT detectors were tested using heavily-attenuated pulses of THz radiation from the UCSB Free-Electron Lasers at 1.53 and 2.0 THz, as well as cw radiation from a molecular gas laser at 1.6 THz. THz signals were detected for bath temperatures ranging from 10K to 120K.

For pulses with sub-ns turn-on and several ns duration,[7] amplifier- and oscilloscope-limited rise-times of ~1 ns were observed. These will be described in more detail elsewhere.

Fig. 3 a shows the predicted intersubband resonance frequency for the coupled quantum well structure studied here at an electron temperature of 70K and a charge density of 1.3 x 10^{11} cm^{-2} as a function of dc electric field. The bath temperature was 15K for these measurements, with electrons warmed to 70K by the source-drain bias. Insets show schematically the coupled quantum wells and minimum subband energies near zero field (middle) and at nonzero fields of equal magnitude but opposite polarity (sides).

Fig. 3b shows the photocurrent response of one device to 5 µs pulses at 1.53 and 2 THz as a function of DC electric field in the growth direction (applied via voltages to front and back gates). For both frequencies, and for all devices studied, a characteristic double-peak structure is observed. The positions of the peaks in the photocurrent are close to those predicted by the self-consistent calculations, shown by the arrows in Fig. 3a. The observations of these double peaks confirms that the dc electric field tunes the detector resonance through the laser frequency. The antenna was designed to be resonant at 1.6 THz. Hence the photocurrents induced near 2 THz are significantly smaller than those induced at 1.53 THz.

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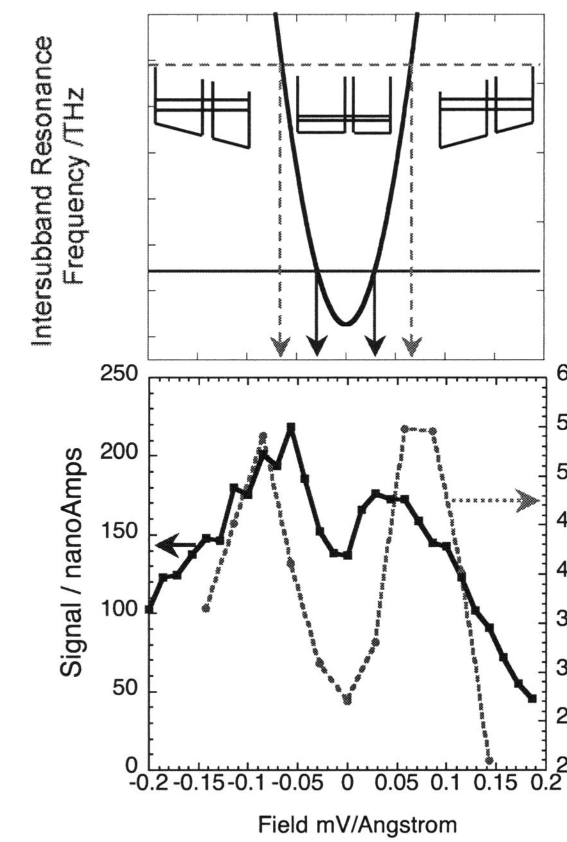

Fig. 3: (a) Intersubband absorption frequency vs DC electric field computed by solving Schrödinger and Poisson equations self-consistently for electron temperature 80K. Horizontal lines correspond to laser frequencies1.53 and 2 THz, vertical lines to electric field at which resonant intersubband absorption is predicted. (b) Photocurrent vs. DC electric field for excitation with 1.53 THz (solid blue) and 2 THz (dotted red).