High Speed Terahertz Modulation from Metamaterials with Embedded High Electron Mobility Transistors

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Abstract

We have designed and demonstrated the performance of a novel terahertz (THz) device resulting from hybridization of metamaterials with pseudomorphic high electron mobility transistors (HEMTs), fabricated in a commercial gallium arsenide (GaAs) process. Monolithic integration of transistors into each unit cell permits modulation at the metamaterial resonant frequency of 0.46 THz. Characterization is performed using a THz time-domain spectrometer (THz-TDS) and we demonstrate modulation values over 30%, and THz modulation at frequencies up to 10 megahertz (MHz).

1. Introduction

In recent years demonstration of frequency agile and tunable metamaterials have shown great potential for applications. By implementing Schottky diodes other research has achieved both spatial [1] and phase modulation [2]. Another area of significant research is the use of two-dimensional electron gases (2DEGs) in high electron mobility transistors and their interaction with THz waves [3, 4]. In this report we demonstrate a hybrid HEMT / metamaterial device that utilizes monolithic integration of transistors at the metamaterial unit cell level and is able to perform as an intensity modulators at terahertz frequencies with switching speeds up to 10 MHz.

2. HEMT / Metamaterial Design

The metamaterial geometry used in this work is based on the electric split-ring resonator (ESRR), and a detail of the unit cell is shown in Fig.1(a). The line width of the metamaterial is 4 μm and the split gap is 3 μm. The metamaterial had the dimensions of 42 μm wide by 30 μm in height. A periodic array of these unit cells as shown in Fig.1(b) was fabricated, with period of 55 μm × 40 μm, and a total size of 2.75 × 2.6 mm^2 with 3200 elements total. Metamaterial elements are fabricated on a 100 μm thick semi-insulating (SI) GaAs substrate.

A HEMT lies underneath each of the split gaps of the metamaterial element, (two per unit cell), as shown in cross-section in Fig.1(c). The gate length is 0.5 μm and has a width 5 μm for each device. The HEMT is constructed using pseudomorphic undoped InGaAs and a lightly doped Schottky layer, each 13 nm thick, creating a heterojunction. A 2DEG is formed in the undoped InGaAs channel layer as predicted by the band diagram at the interface (Fig.1(d)) [5]. Unlike traditional FETs, this channel is formed in

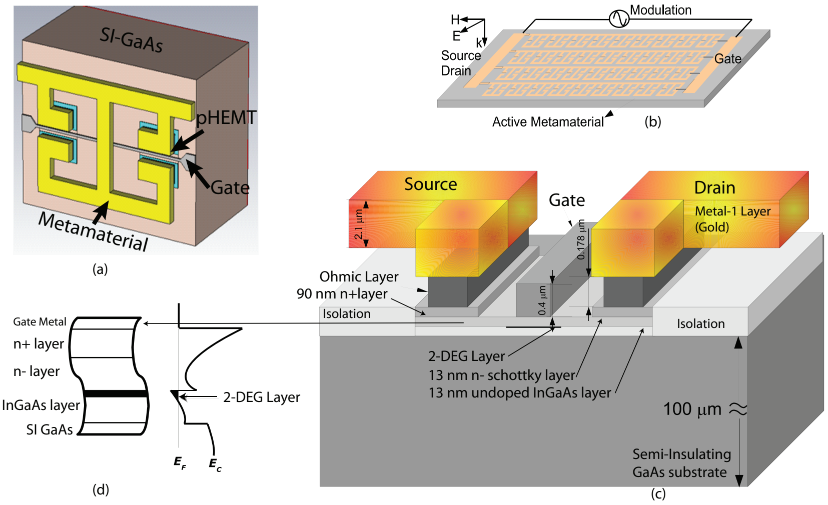

Fig. 1: Design and structure detail of the HEMT based electronically controlled THz metamaterial modulator. (a) Single unit cell of the metamaterial element, as modeled for simulation. The HEMT is identified and lies under each split gap of the metamaterial. (b) Schematic depicting the entire HEMT / metamaterial device, and the polarization orientation of the incident THz wave is shown. (c) Cross-sectional view of the HEMT / metamaterial device in proximity to the split gap. (d) Band diagram detailing the 2DEG layer in the undoped InGaAs at the interface with the Schottky layer.

an intrinsic (undoped) crystal, resulting in very high mobility ($\sim$ 3000 cm^2/V·s) and charge density ($\sim 1.5 \times 10^{12}$ cm^{-2}) at room temperature, thus enabling fast conduction even at THz frequencies. The same metal layer which is used to form each metamaterial is also used to connect each element together within the same row. At the perimeter of the device each row is connected vertically using the ohmic layer and all elements are connected to a single bond pad to provide DC bias voltage for the drain and source of the HEMT. The gates for all HEMTs are connected in a similar fashion to a single bond pad which provides the DC bias voltage for the gate.

3. THz Modulation Experimental Results

The device was characterized using a THz-TDS with the incident time-domain THz electric field ($\vec{E}_i(t)$) polarized along the split gap to drive the metamaterial elements into resonance. In order to elucidate the switching ability of the terahertz metamaterial, we plot the differential transmission, defined as $D(\omega) = [T(\omega)_{V_{GS}} - T(\omega)_{V_{GS}=0V}]/T(\omega)_{V_{GS}=0V}$ in Fig. 2(a). The black curve of Fig. 2(a) is two successive transmission measurements divided by each other, both at V_{GS} = 0 V, thus representing the frequency dependent noise. For a differential transmission of V_{GS} = -0.5 V, cyan curve of Fig. 2(a), $D(\omega)$ is relatively flat with deviations of about 5% or less, except at a frequency of 0.46 THz, where a value of -13% is observed. This minimum in differential transmission at 0.46 THz is seen to increase for increasing V_{GS}, until at V_{GS} = -3.0 V were a value of $D(\omega)$ = -33% is observed.

We demonstrated the ability to switch the THz waveform by adjusting the gate bias voltage of the HEMT with respect to the drain and source (V_{GS}). We now turn toward demonstration of high speed dynamic modulation and utilize a THz-TDS using a Photoconductive Antenna (PCA) emitter and detector. The standard mechanical chopper often utilized in a TDS system was replaced with the HEMT / metamaterial modulator which serves the same function as the mechanical chopper with the important distinction that now only a narrow band of frequencies about the metamaterial resonance is modulated. Therefore, the data has to be interpreted differently than the static case. A square-wave bias, alternating between -1.1

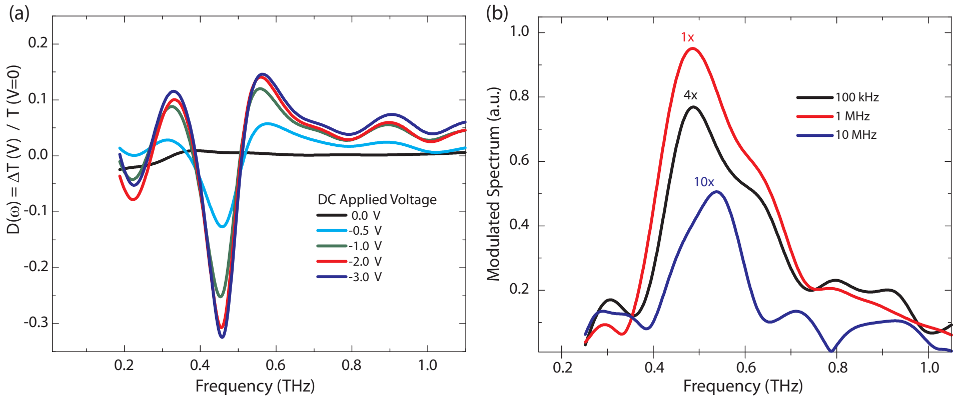

Fig. 2: (a) Frequency dependent differential transmission as defined in the text for the HEMT / metamaterial device as a function of bias. (b) Modulated spectra calculated from time domain data for modulation at frequencies of 100 Hz, 1 MHz and 10 MHz.

V and 0 V, was applied to the gate of the HEMT with respect to the source and drain. The same square wave signal was applied to the reference input of the lock-in amplifier.

We plot in Fig. 2(b) the spectrum for three different modulation frequencies, 100 kHz, 1 MHz and 10 MHz as obtained from Fourier transforming the measured time-domain data. It can be seen that the peak of the spectrum lies at 0.46 THz indicating modulation of the metamaterial resonance. Bandwidth of the spectrum remains relatively unchanged between 100 kHz and 1 MHz, and the amplitude of the spectrum increases. At a modulation rate of 10 MHz the bandwidth is observed to decrease a bit and the amplitude falls of from values observed at 1 MHz. The spectrum amplitude has a non-monotonic dependence as a function of frequency that can largely be attributed to the THz-TDS setup itself.

4. Conclusion

We have demonstrated a HEMT / metamaterial device capable of modulation of THz radiation at frequencies up to 10 MHz, and modulation depths of up to 33% at 0.46 THz with all electronic control. We achieved monolithic integration of a total of 2×10^4 active transistors at the metamaterial unit cell level. This work demonstrates a new path for construction of high speed terahertz electronic devices.

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