Hot-electron micro&nanobolometers based on low-mobility 2DEG for high resolution THz spectroscopy

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Abstract. The results on design, fabrication, and characterization of a hot-electron bolometer (HEB) based on the low-mobility two-dimensional electron gas (2DEG) in a AlGaN/GaN heterostructures show that our HEBs have high coupling to incident THz radiation due to the Drude absorption. Significant heating by THz radiation is realized due to the small value of the electron heat capacity. A low contact resistance achieved in our devices ensures that the THz radiation couples primarily to the 2DEG. Due to the small electron momentum relaxation time, the real part of the 2DEG sensor impedance is \(\sim 50-100 \, \Omega\), which provides a good impedance match between the sensor and antenna. Currently the room temperature responsivity of our devices reaches \(\sim 0.04 \, \text{A/W}\) at 2.55 THz along with a noise equivalent power \(\sim 5 \, \text{nW/Hz}^{1/2}\) at room temperature.

1. Introduction and background

THz heterodyne receivers currently use Schottky diodes, Superconductor-Insulator-Superconductor (SIS), plasma electronics detectors, and superconducting hot-electron-bolometers.

For a long time, Schottky diode mixers were used in receivers for frequencies up to THz range. The main advantage of these mixers is the possibility of room temperature operation. However, the key problem is that the Schottky diode requires high LO power for its operation as a mixer, in addition, they have rather poor sensitivities above the 1-2 THz range.

Superconductor-Insulator-Superconductor (SIS) tunnel junctions operate at liquid helium temperatures. However, these devices have high sensitivity only at frequencies below the superconducting energy gap. Above the superconducting gap frequency (e.g. \(~1.2\) THz for NbTi), the performance of SIS mixers reduces dramatically.

Developed a decade ago, superconducting hot electron bolometer (HEB) mixers are currently the devices of choice for the frequencies above 1 THz. The heterodyne mixing process is based on temperature dependence of the bridge resistively in the transition (resistive) state. The IF bandwidth is determined by the inverse electron cooling time, which can be varied from the electron-phonon relaxation time in long wires to the hot-electron outdiffusion time in short bridges. Currently, NbN devices show the best sensitivity, such as a noise temperature, \(T_n\), of 750 K at 1.9 THz and 950 K at 2.5 THz, in combination with an IF gain bandwidth of \(~6\) GHz. However, they require deep cooling, down to helium temperatures. Cryogenics requirements are a main obstacle for these devices.
Two-dimensional electron gas in semiconductor heterostructures was identified as a promising medium for heterodyne mixing in early 90s [1]. Up until now the only material, which has been pursued in view of its availability, is AlGaAs/GaAs. However, it is currently understood, that parameters of AlGaAs/GaAs heterostructures (high mobility and low carrier concentration) do not allow for achieving of a reasonable coupling to THz radiation above ~1THz [2].

2. Results
We investigate capabilities of a novel fast (picosecond) THz detector for use in advanced heterodyne receivers, operating from liquid nitrogen to room temperatures. The detector operation is based on the effect of electron heating of low mobility two-dimensional electron gas (2DEG) in micron/submicron patterned GaN heterostructures [3].

The GaN heterostructures were grown by memory enhanced metal-organic chemical vapor deposition (MEMOCVD®) on two inch diameter (0001) sapphire substrates (see Fig. 1). First, a 200 nm undoped AlN layer was grown on the substrate, this layer was grown to reduce surface roughness on the sapphire substrate and to prevent propagating of defects upward. After that, a 2.5 μm non-intentionally doped GaN buffer layer was grown. Then a 1 nm high Al-content AlGaN spacer layer and a 9.5 nm Si-doped Al₀.₈₈Ga₀.₁₂N top layer were deposited. Finally, the samples were covered with SiO₂ to avoid oxidation of Al in the top layer. The room temperature electron mobility and concentration were extracted using Hall and Van-der-Paw measurements.

A combination of the short electron mean free path with high electron density of 2DEG provides a sheet resistance of 200 - 300 Ω/□ that meets the requirements for the impedance matching between conventional THz antennas and a 2DEG sensor. Three different wafers with a different level of doping were grown for our devices.

The wafers were processed into mesa structures by photolithography and dry etching in a SiCl₄/Argon mixture plasma. Prior to the dry etching process, the samples were prepared by organic cleaning procedure, using trichloroethylene, acetone and methanol. A Ti/Al/Ti/Au metal stack having a thickness of 25/70/50/100 nm was deposited by using an e-beam evaporator after the etching process, followed by rapid thermal anneal (RTA) at 850 °C in a N₂ ambient to form ohmic contacts. Finally, an antenna made of a 200 nm Ni/Au was deposited on the top of the structure. The antennas deposited on the ohmic contacts were used also as extended contact pads by the external read-out circuit.
Our devices discussed here have three types of broadband antennas covering a range of frequencies from 1 THz to 4 THz: (1 and 2) a regular bow-tie antenna (figure 2), (3) a spiral antenna with ohmic coupling (figure 3), (4) a bow-tie antenna with a capacitive coupling (figure 4). In the devices with ohmic coupling, an antenna was deposited on the top of the ohmic contacts, which transfer current from the antenna to the 2DEG. Device 1 had the mesa area of $40 \times 40 \mu m^2$ (marked by red dash line in figure 2a) and the channel area $L \times W = 2 \times 2 \mu m^2$ (see figure 2b). Device 3 with ohmic contacts had a broadband spiral antenna with 2DEG channel of $2 \times 10 \mu m^2$ (figure 3).

Device 4 used capacitive coupling and split-gate patterning of the sensor (figure 4) with the bow-tie antenna not having ohmic contacts to the 2DEG and with the mesa tapered from the contact sides towards the antenna terminals (figure 4b). The narrow $2 \mu m \times 4 \mu m$ channel between the bow-tie antenna apexes created a current constriction area. The THz electric field induced in the gap between the antenna apexes penetrated into 2DEG layer and heated the electron gas in the channel. The design with capacitive coupling allows one to avoid significant technological problems related to fabrication of low-ohmic contacts. In addition, the antenna’s bows may be used as side split-gates to decrease the channel width by applying a negative potential to the gate. This design allowed us to control and optimize the channel width.

The results of the measurements for Devices 1 and 2 are shown in figure 5. As seen, the Device 1 responsivity reaches 14 mA/W at a bias of 10 mA. It is approximately 1.5 times greater than that for Device 2, which is in good agreement with the interpretation in terms of the parameter $\lambda^2/(L \times W)$, since the ratio of the areas of these devices equal to 2. The small difference can be accounted for the different antenna impedances. For the polarization along the arrow on Fig. 4b, the photoresponse is.
five times lower because the antenna did not develop voltage for this polarization of THz radiation, and the entire response, was due to the direct absorption of THz radiation by the 2DEG.

![Image](image_url)

**Figure 4.** Image (a) and schematic diagram (b) of Device 4 with capacitive coupling, (b) the mesa is shaped in a form having a narrow 2DEG channel between the apexes of the bow-tie antenna.

![Graph](graph_url)

**Figure 5.** Responsivity versus bias current for Devices 1 and 2.

The THz photoresponse of Device 3 was measured at a laser power of 58 mW/cm² using the chopping frequency of f = 1 kHz. The THz response of this device was three times greater than the response of Device 1 and reaches 40 mA/W at a bias current of 8 mA. The enhanced response may be explained by the small areas of the mesa and of the channel in this device.

The device 4 antenna had the flare angle of 60°, impedance of 85 Ω, and gain of 5 dB. The DC resistance of the device was 1.9 kΩ. The following experimental settings were chosen for the device characterization. The laser power was 50 mW/cm² and the chopping frequency was 355 Hz. For the polarization along the arrow on figure 4b, the photoresponse was two times smaller than for the polarization in the direction of the antenna that is perpendicular the arrow on figure 4b. For the first polarization, the antenna does not enhance coupling to 2DEG. However, the 2DEG itself may operate as an antenna, because the 2DEG channel had a shape of the bow-tie antenna with a flare angle of 120°. The results of the measurements for the second polarization of THz radiation are shown in figure 6. As it is seen from figure 6, the response of Device 4 with capacitive coupling is similar to those shown in figure 5.
We conducted first measurements of the 2DEG HEB mixer frequency bandwidth. Because the bandwidth of a HEB mixer does not depend on frequencies of the mixing waves, we used available equipment: two Gunn diodes, where one was used as a local oscillator and the other diode as a source. The local oscillator (LO) frequency was tunable between 81 and 98 GHz and the signal source (RF) was fixed at 81 GHz. The LO and RF powers were brought together through a 6 dB directional coupler followed by a calibrated attenuator. Since all measurements were done at 300 K the cryostat was used only for sample mounting purpose, but in the next experiments with QCL we may use it for low temperature experiments. The LO and RF signals were coupled to the 2DEG mixer by placing the mixer at the open end of the waveguide. Figure 7 shows the normalized IF power versus an IF frequency measured at 300K for Device 3. The 3 dB bandwidth defined by $BW = 1/2\pi\tau$ was found to be equal to 2 GHz that correspond to the maximum bandwidth achievable with our setup. This result shows that the electron cooling time is shorter than 100 ps.

In summary, the feasibility of 2DEG GaN hot electron bolometer (HEB) for THz heterodyne sensing in the range 1-4 THz has been demonstrated. Hot-electron bolometers based on the low-mobility two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures have been designed and fabricated. Electrical, optical, thermal, and THz characterizations of our devices show that the low mobility ($\mu \approx 2000$ cm$^2$/Vs) and the corresponding short electron momentum relaxation time provide a strong coupling between the 2DEG and incident THz radiation due to the Drude absorption. A high electron concentration ($n \sim 10^{13}$ cm$^{-2}$) in 2DEG structure provides the real part of the 2DEG sensor impedance of $\sim 50-300$ $\Omega$, which allows for impedance matching between the sensor and conventional broadband THz antennas. Our estimates show that the responsivity and NEP of our devices can be significantly improved by 1) further reduction the sensor area, 2) growing GaN structures with increased doping to further increase carrier concentration and reduce momentum relaxation rate. This will improve the impedance match between the antenna and 2DEG sensor at THz frequencies.
Figure 7. Normalized IF output power versus an intermediate frequency for the mixer prototype.

References

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