Ballistic deflection transistors and their application to THz amplification

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Abstract. We present implementation of recently proposed ballistic deflection transistors (BDTs) as THz amplifiers. BDT is a planar device based on InGaAs/InAlAs/InP heterostructure with quasi-ballistic transport obtained in the two-dimensional electron gas layer that facilitates ultra-short transit time and high performance needed for THz-range circuitry. The BDT performance is optimized through its structural modification and the use of high-k dielectrics. Our time-domain, electrical transient measurements demonstrate sub-THz switching performance of a BDT with a ~1-µm-wide channel. Independently, circuit simulations using experimental parameters of BDTs with a channel width of 430 nm and with the BDTs themselves connected as a multi-stage travelling-wave amplifier, designed for 6-dB gain, predict a 2.7-THz bandwidth with a gain flatness of ±0.3 dB.

1. Introduction

The scaling limit of CMOS technology has given birth to other alternative novel devices. Some devices offer improved speed, some promise unmatched power efficiency, while others are reconfigurable at runtime to offer both versatility and robustness [1]. In addition, advanced nanofabrication techniques and novel material configurations have lead to devices in which the active region is smaller than the mean free path of electrons at room temperature. These devices are ballistic in nature, since the main scattering electrons encounter is with the designed device geometry [2]. In the same context, our group has introduced a ballistic deflection transistor (BDT), which is proposed to work at THz frequencies at room temperature [3]. The BDT exploits the very nature of a two-dimensional electron gas (2DEG) layer, where electrons can travel without virtually any scattering and achieve very high velocities of the order of 10^8 cm/s, what is 2.5 times faster than electron transport in silicon. Given the ultralow capacitive design, due to the fully planar device geometry, initial estimates of the unity-gain current frequency \( f_T \) > 1 THz for the BDT fabricated with a 430 nm gate width [3].

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The main contribution of this work is not only to validate the feasibility of the BDT operation in the THz range through simulations, but also to demonstrate the usefulness of the time-resolved optoelectronic spectroscopy, as a tool for experimental characterization of THz-bandwidth devices.

2. BDT description and operation

The BDT is a six-terminal coplanar structure etched into an InGaAs 2DEG. The device consists of a grounded electron source, left and right gates, and three biased drains. Figure 1 shows a SEM image of the top-view of BDT with the experimental set up. The top-left (VLD) and top-right (VRD) ports are drain ports, bottom-left (VLG) and bottom-right (VRG) ports are gates, top port (VTD) is a bias port that controls gain, and the bottom port (VSS) is the source. Electrons in the high mobility 2DEG are provided by the δ-doped layer, which is separated by the undoped spacer, to reduce the interaction with remote impurities.

![Figure 1. SEM image of top view of BDT with channel width \( c = 240 \) nm and trench width \( t = 100 \) nm. Top-left (VLD) and top-right (VRD) ports are drains, bottom-left (VLG) and bottom-right (VRG) ports are gates. Top port (VTD) is a bias port that controls gain, and the bottom (VSS) port is the source.](image)

A typical, room temperature transfer curve is shown in figure 2. The current rises and pinches down with gate voltage. This shape of transfer curve makes a BDT suitable for frequency doubling. A simple operational mechanism of BDT is shown in the inset of figure 2, which exhibits that when the electron current moves along the left drain, transistor registers logic “1” at left drain and logic “0” at right drain and vice-versa. The gate control over the channel can be attributed to three effects: classic channel pinch-off due to the field effect, an electron steering due to the gate bias, and deflection due to the presence of a centre triangular deflector. The steering effect implies that flowing electrons encounter a lateral field directing them towards one output drain or the other, depending on gate bias. Pinch-off can be observed when a strong bias depletes the channel completely. Interaction of electrons with right or left side of the deflector helps electrons in moving towards the corresponding drain. A detailed explanation of the BDT operation can be found in [4] and [5].

3. THz amplification using BDTs

For THz amplifier simulations, we have designed an 8-stage BDT traveling-wave amplifier with 15 BDTs in each stage, as shown in figure 3. BDTs were interconnected with the 185-Ω characteristic impedance coplanar waveguide for both the gate and the drain lines. The length of each differential transmission line was 320 μm, feasible for an on-chip implementation. The actual BDT equivalent circuit parameters were derived based on experimental performance of a BDT transistor with the 430-nm-wide channel, including both capacitive and resistive parasitics. A large number of amplifying stages were needed to achieve a large enough (in our case 3 mS) total transconductance for the assumed total gain of 6 dB.
Simulation results are presented in figure 4 and demonstrate that our amplifier achieved a 2.7-THz bandwidth with a gain flatness of ±0.3-dB. The return loss was better than −10 dB up to 2.5 THz and the gain-bandwidth product reached 10.8 THz. The inset shows the impedance mismatch reduction after every stage until the match was achieved at the stage 8. Although the device representation in our simulations has been based on low-frequency BDT parameters, our studies clearly demonstrate that BDT amplifiers have a high potential to achieve the THz-level performance. The latter observation has been independently supported by the Monte Carlo (MC) simulations [6]. Finally, we stress that in the studied amplifier, its gain was limited by the transconductance of our present-day BDTs and we expect a dramatic improvement by introducing BDT nanostructures with the channel width below 200-nm.

![Figure 3](image)  
**Figure 3.** Schematics of a traveling wave THz amplifier based on a sequence of BDTs. The actual, simulated amplifier was a multi-tap structure.

![Figure 4](image)  
**Figure 4.** Simulated frequency response of the S12 parameter and input matching (inset).

### 4. Time-domain characterization of BDTs

Figure 5 presents our integrated, "experiment-on-chip" setup [7] that enables picosecond, time-domain, or, equivalently, THz-bandwidth characterization of ultrafast electronic devices, such as a BDT shown schematically at the bottom of the top panel. The top panel shows the laser system with two optical beams (excitation pulses) aimed at the gaps in the coplanar waveguide structure, acting as the optoelectronic transducers. Next, our electrical excitation transients (schematically shown as red pulses) are applied to the BDT gates and the resulting output signals were sampled using electro-optic (EO) transducers at the positions corresponding to the red dots. As a reference, we also time resolved the input electrical transients at the points (blue spots) just before the BDT, also using the EO method [8]. The actual input and output transients are shown in the bottom panel and are indicated by the arrows. The input pulse exhibits a strong, negative reflection from the BDT due to a very large impedance mismatch between the coplanar waveguide and the BDT [7]. Finally we note that the BDT output pulse has a ~230 GHz bandwidth, what is expected from an ~µm-size-channel BDT with semiballistic transport, used in this experiment and, in fact, agrees well with MC simulations for a ~800-nm-channel BDT. Based on MC simulations, a scaled-down BDT should achieve sub-ps performance.
Figure 5. Schematics of an experimental setup (top panel) for OE generation of electrical transients incident on the BDT, measured at the position corresponding to the blue dots, and the EO detection of the output signals (position red dots), transmitted through the device. The bottom panel shows the actual transients recorded using the EO sampling method.

6. Conclusions
We have demonstrated usefulness of a BDT nanostructure for THz frequency range applications at room temperature. Preliminary evaluations, including MC simulations have shown the BDT ultrahigh operating speed and reduced gate capacitance. The latter input was used to build a circuit model working as multi-stage, multi-BDT traveling-wave amplifier. In its simplest implementation, the amplifier achieved THz-level performance with a 2.7-THz bandwidth for a 6-dB gain and the gain-bandwidth product of up to 10.8 THz. In addition, using an optoelectronic time-domain spectroscopy method we have experimentally demonstrated THz switching of BDTs incorporated into coplanar waveguides and excited by picosecond electrical input transients.

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