Picosecond electric pulse excitation of three-branch ballistic nanodevices

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Abstract. Picosecond electrical pulse excitation of the ballistic three-branch junctions (TBJs) was performed to investigate the electrical response at terahertz frequencies. The generation of picosecond electrical pulses and the signal detection with sub-picosecond temporal resolution were achieved by a photoconductive switch and the time-resolved electro-optical sampling technique, respectively, with the help of the femtosecond Ti:Sapphire laser system. The electrical response of a TBJ rectifier to the 1.75-ps-wide incident pulse was successfully measured and its frequency spectrum was not degraded in the tested frequency range, as compared to the incident excitation.

1. Introduction

Electron devices utilizing ballistic electron transport have been regarded as the most suitable devices for the future high-speed electronics because of their predicted terahertz (THz) bandwidth [1]. One class of such ballistic devices is nanoscale three-branch junctions (TBJs) fabricated in 2-dimensional electron gas (2DEG) heterostructures [2,3]. Because of the extremely small internal capacitance of the TBJ, its frequency response is free from the RC charging time limitations, contrary to the conventional electron devices. This advantage gives rise to a hope of building THz electronics from TBJs. THz operation of the TBJs has been demonstrated by the Monte Carlo simulations [4], however, experimental verifications have been limited to the GHz frequency band [5], due to the lack of proper testing tools. Therefore, developing a testing tool with a bandwidth reaching the THz frequency band is desired to assess the ultimate performance of ballistic devices. In addition, exploring the ultrafast response of ballistic devices is interesting in its own right, because it is expected to observe new physical phenomena such as the kinetic inductive effect [6] in a time scale shorter than the mean scattering time. Although the kinetic inductive effect is negligible in conventional nonsuperconducting electron devices, it could govern the ballistic electron transport in the THz frequency regime.

In this communication, we present an experimental chip consisting of a transmission line structure, which integrates both a photoconductive (PC) switch and a ballistic TBJ rectifier under test. Femtosecond optical pulses were used to excite the PC switch and trigger a single-picosecond voltage transient applied to the TBJ rectifier, while the output of the rectifier was read with the help of an ultrafast electro-optical (EO) sampler. The above arrangement allowed us to investigate the ultrafast electrical response of the TBJ devices and demonstrate their applicability for THz electronics.
2. Integrated system for the generation and detection of the picosecond electrical pulses

In figure 1(a), schematics of our monolithic chip for the picosecond pulse excitation of the TBJ structure and the subsequent read-out by the EO sampler are illustrated. A PC switch is a pulse generator that consists of two metal electrodes deposited on a photoconductive substrate and separated with a micrometer size gap [7]. Since the photoconductive substrate becomes conductive only when it is illuminated by light, one can excite an electrical transient by illuminating the DC-biased switch gap with a short laser pulse. In our experiment, a 50-nm-thick InAlAs layer that was grown on an InP substrate by molecular beam epitaxy (MBE) was used for the photoconductive material and a train of 100-fs-wide optical pulses generated by a commercial, mode-locked Ti: Sapphire laser were employed for the optical excitation.

As is shown in figure 1(a), the PC switch is incorporated into a coplanar waveguide (CPW), which allows the delivery of the electrical pulse to the device under test (DUT), which in our case is a TBJ rectifier consisting of two TBJs in parallel as shown in figure 1(b). The TBJ is a 3-terminal device that exhibits a nonlinear transfer curve originated from the ballistic electron transport [3]. It has been shown that the nonlinear response makes the TBJs work as rectifiers or logic gates [1].

For the detection of the ultrafast transient signal, we have employed an ultrafast EO sampler [8] consisting of an EO transducer (a LiTaO₃ crystal overlaying the transmission line) and optics system as a polarization analyzer. The EO transducer converts the electrical field signal, traveling in the CPW line and coupled to the EO crystal, into the change of polarization state of the optical sensing pulses penetrating the EO crystal and reflected from the dielectric mirror at the bottom. By using a linearly polarized incident light and two cross-polarized polarizers, the EO sampler acts as an optical intensity modulator for the sensing beam. It has been verified that EO samplers based on the LiTaO₃ crystal exhibit the bandwidth that exceeds 1 THz [9]. Finally, we stress that the EO sensing position can be changed by moving the sensing crystal along the CPW line (e.g., in front of the DUT), so both the incident transients and the ones transmitted by the DUT can be measured with a sub-picosecond temporal resolution.

3. Fabrication

The fabrication of the integrated chip started with a modulation-doped In₀.₅₃Ga₀.₄₇As/In₀.₅₂Al₀.₄₈As heterostructure, grown by MBE on a semi-insulating InP substrate. The resulting 2DEG layer was approximately 60 nm beneath the surface, and its room temperature mobility \( \mu \) and electron sheet
density \( n_e \) were 1.1 m\(^2\)/Vs and 4.1x10\(^{15}\) m\(^{-2}\), respectively. To define the geometry of the Y-shape mesa, electron beam lithography and subsequent ion-mill etching were used, resulting in 130-nm-deep etching and bringing the InAlAs buffer layer that was used for PC switch to the surface. Then, a stack of Ni/Ge/Au was deposited and annealed at 420 °C for 30 seconds in Ar/H forming gas for the ohmic contacts. Finally, the CPW layer was formed by the electron beam lithography and lift-off of a 200-nm-thick Au layer. The width of the CPW’s central conductor and its separation from the ground planes were both 30 μm. The gap of the PC switch was chosen to be 25 μm.

![Figure 2. EO measurement of a voltage transient generated by the PC switch.](image)

4. **Picosecond electrical pulse excitation of TBJ rectifier**

In the first phase of our studies, we performed EO characterization of the picosecond electrical pulses from the PC switch by fabricating a test structure identical to the one shown in figure 1(a) but without the DUT. Figure 2 presents a transient voltage signal generated by the PC switch, illuminated with 2 mW of optical power and biased at 9 V. The main pulse has the full-width at half-maximum (FWHM) of 1.75 ps and the amplitude exceeding 0.5 V.

In the complete test chip, which included the DUT, the transient waveforms both before (incident signal) and after (transmitted signal) the TBJ rectifier were measured, as is shown in figure 3(a). Looking at the incident waveform, the first pulse is a somewhat dispersed (broadened) switch pulse shown in figure 2 and it is followed by the second pulse, which is a reflection from the DUT. The latter observation was experimentally confirmed by measuring the time separation \( \Delta t \) between the two peaks while moving the sensing positions (data not shown). It was observed that \( \Delta t \) increased linearly with the distance \( \Delta x \) of the sensing position from the TBJs. We also calculated the propagation velocity \( v_g \) from the slope of the \( \Delta x \) vs. \( \Delta t \) dependence, which gave \( \approx 1.0x10^8 \) m/s, a value reasonable for our CPW. Another observation is that the amplitude of the reflected pulse, after background subtraction, is close with that of the incident pulse, which indicates that a large portion of the incident signal was actually reflected at the CPW/DUT interface. This large reflection is a consequence of a significant impedance mismatch at the CPW/DUT plane, due to the fact that the characteristic impedance of the CPW was 62 Ω, while the TBJ rectifier input impedance was \( \approx 20 \) kΩ. Thus, the effective excitation signal coupled into the DUT must have been only on the 1 % level of the total incident signal.

The shape of the transmitted signal in the case of unbiased TBJ rectifier is shown in figure 3(a). We note two prominent features: (1) its amplitude is \( \approx 22 \) mV, corresponding to only a few % of the height of the incident pulse; (2) the pulse has an oscillatory shape. The small amplitude is again caused by the impedance mismatch that results in a small power coupled into the TBJs. On the other hand, the negative dip of the transmitted pulse strongly suggests that there exist some reactive elements in the DUT structure. This observation was confirmed by the fact that a time derivative of the incident pulse, shown as a dotted line in figure 3(a), followed almost exactly the transmitted pulse shape. The origin of the reactive elements is most likely the capacitive coupling among the funnel-shape access regions between the nano-channel and the ohmic contacts, as well as external coupling of the TBJ rectifier to the CPW, as it was discussed in the equivalent circuit analysis in [5].
To show the advantage of the implemented technique, the Fourier transform spectra of the transient signals are shown in figure 3(b). The spectrum of the incident pulse reaches almost 1-THz bandwidth and is limited by the PC switch response time. The spectrum of the transmitted pulse has the frequency dependence similar to the incident pulse, resulting in a constant amplitude ratio within the bandwidth as shown in the inset of figure 3(b). The constant ratio indicates that the TBJ rectifier does not intrinsically degrade the frequency response in the tested sub-THz frequency range. Finally, it is worth to mention that further extension of the system bandwidth is possible by modifying the PC switch geometry into a metal-semiconductor-metal interdigitized structure with a sub-micrometer gap [10] to realize electrical excitations with over 1-THz bandwidth.

Acknowledgements
This work was supported by the NSF NIRT grant ECS-0609140, ONR grant N00014-08-1-0093, and AFOSR grant FA9550-07-1-0032, and a NYSTAR Grant to the UR CAT-CEIS. The test structures were fabricated at the Cornell NanoScale Science and Technology Facility, a member of NNI Network, which is supported by the NSF grant ECS-0335765.

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