Ballistic Transport Investigation and the Ballistic Deflection Transistor

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Principal Investigators: Martin Margala, Marc Feldman

Users: Quentin Diduck, Hiroshi Irie

Affiliation: Electrical and Computer Engineering Department, University of Rochester
Primary Funding: Office of Naval Research Grant N000140510052, and NSF Grant ECS-0609140
Contact: margala@ece.rochester.edu, diduck@ece.rochester.edu, irie@ece.rochester.edu

Abstract
In this work, we have been investigating the properties of non-linear ballistic transport and optimizing the design of a novel device, the ballistic deflection transistor (BDT). The electron steering effect required for an operational BDT has been demonstrated. A T-branch junction is also investigated.

Research Summary
The BDT utilizes a novel non-linearity first discovered by Song et. al. [1, 2], and is best understood as a shift in energy created by an artificial scattering mechanism rather than a PN junction. We are currently developing a transistor based upon this non-linearity in combination with electric gates that direct electrons to the appropriate portion of the artificial scatter. The general structure of the device is a cross-shaped structure with a triangular section removed from the intersection of the cross, with two lateral gates on the longer portion of the cross. The removed triangular section acts as the artificial scattering mechanism, and in combination with the gates enable direction of electrons to either lateral channel. A bias current is applied across the long section of the device much in the same way as an electron gun in a CRT, with the gates acting as the steering field. Figure 1 presents a scanning electron micrograph (SEM) of a recently fabricated design.

The fabrication of the device begins with the growth of an InGaAs-InAlAs heterostructure on an InP substrate by molecular beam epitaxy. Gold alignment marks suitable for electron beam lithography are created to enable multiple alignment steps. Hard mask formation is achieved by the evaporation of carbon and a thin layer of SiO$_2$ followed by patterning using PMMA resist. Exposed areas are subjected to a CF$_4$ plasma that removes the SiO$_2$, followed by an oxygen plasma that removes the carbon, creating a transfer mask. The etch is achieved using an ion mill. Lateral gates are formed from the semiconductor and are patterned at the same time as the rest of the structure. The contact layer is then formed using Ni-Ge-Au contacts.

Figure 1: SEM image of a ballistic deflection transistor.

Figure 2: Left and right output voltage response to a push pull voltage.
This structure will have several advantages over conventional transistors. The lateral gates only direct current, and are not used to stop the current through the device (though they can deprive a channel of current). This improves the transit time through the device. The general structure of the transistor is essentially a differential pair rather than a single on/off switch, and this increases the compactness of subsequent circuits. Also there is no intrinsic threshold as such; current is always flowing but is controlled between two ports. The switching voltage is a ratio between the bias voltage and gate size, and as such, very low voltage operation is possible (below 100 mV) with noise being the limiting factor. Recent measurements have demonstrated the steering effect, however gain has yet to be achieved (see Figure 2). We are currently modifying the design to reduce the induced built-in potential of the etched regions near the gates. This built-in potential has been shown to be impeding the steering effect and is the cause of the low gain at this time.

In addition to the transistor structure, we are investigating the fundamental properties of ballistic transport. Here we focus on one such device called the T-branch junction (TBJ) [3]. It has a large nonlinear input-output transfer function on the order of unity. Recent experiments [4] indicate that the intrinsic nonlinearity persists at high frequencies, to at least a terahertz. Therefore the nonlinear current mechanism of the TBJ could in principle be used to build electronic circuitry at unprecedented high frequencies. An SEM picture of one of our TBJs is shown in Figure 3 and typical electrical results are shown in Figure 4. We see that when a push-pull voltage \( \pm V \) is applied, the central probe voltage \( V_C \) is always zero or negative. If the TBJ were ohmic / diffusive, we would expect \( V_C = 0 \) at all \( V \). But to a good approximation, \( V_C \) in Figure 4 can be described as zero for \( V < 200 \) mV, a straight line with slope near \( \pm 1 \) for larger \( V \), and a gradual transition region between. The \( \pm 1 \) slope implies that \( V_C \) is to some extent pinned to the voltage at which electrons enter the T-bar, from whichever side. Also, the current through the top of the T is proportional to \( V \) (apparently ohmic) until it appears to partially saturate at the same transition region. This correlation between current saturation and onset of negative \( V_C \) is observed with all device geometries and temperatures. This strongly suggests that the two phenomena are caused by the same mechanism.

Our experiments and device structures have demonstrated that non-linear devices can be fabricated using ballistic transport. TBJs exhibit a near unity voltage-in over voltage-out response. The BDT has shown that it is possible to create a steering effect by using lateral fields without depleting the channel; as well it has been shown that the artificial scattering objects can perform as an active load in this device. In the near future, we expect to produce a BDT with gain.

**References**


