Novel room-temperature functional analogue and digital nanoelectronic circuits based on three-terminal ballistic junctions and planar quantum-wire transistors

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Abstract. Three-Terminal ballistic junctions (TBJs) and planar quantum-wire transistors (QWTs) are emerging nanoelectronic devices with various novel electrical properties. In this work, we realize novel nanoelectronic analogue and digital circuits with TBJs and planar QWTs made on In_{0.75}Ga_{0.25}As/InP two-dimensional electron gas (2DEG) material. First we show that a single TBJ can work as a frequency mixer or a phase detector. Second, we fabricate an integrated nanostructure containing two planar QWTs, which can be used as an RS flip-flop element. Third, we make a nanoelectronic circuit by the integration of two TBJs and two planar QWTs. This circuit shows the RS flip-flop functionalities with much larger noise margins in both high and low level inputs. All measurements in this work are done at room temperature.

1. Introduction
Currently, with the fast development of semiconductor fabrication technology, the feature size in the basic circuit components is approaching the nanometer scale. In this length regime, physical limits will prevent the devices with conventional designs from working properly. The demand for next generation nanoelectronic devices and circuits has become the driving force of the research in nanoelectronics community. Several novel device concepts and technologies have been proposed [1]. Among them, three-terminal ballistic junctions (TBJs) and planar quantum-wire transistors (QWTs) are promising because these elements have simple structures, are easy to fabricate and function at room temperature. In this paper, we first demonstrate the basic device principles of the TBJs and the planar QWTs. We then show that a single TBJ can work as a frequency mixer or a phase detector. Finally, we report on the realization of two types of RS flip-flop elements by the integration of nanostructures containing TBJs and/or planar QWTs. All devices in this work are prepared by electron beam lithography and wet etching on a standard In_{0.75}Ga_{0.25}As/InP two-dimensional electron gas (2DEG) material. The electrical measurements show that the fabricated devices operate at room temperature reproducibly with desired...
functionalities. Thus, TBJs and planar QWTs may be used as new building blocks in nanoelectronics.

2. Three-Terminal ballistic junctions and planar quantum-wire transistors

The concepts and device principles of TBJs were theoretically predicted [2] and experimentally verified [3] in 2001. Figure 1 is an atomic force microscope (AFM) photograph of a fabricated TBJ. The left, right and central branches are indicated by L, R, and C, respectively. G stands for the in-plane gate, which was not in use in this work. The distance between the two quantum point contacts (QPCs) of the left and right branches is 170 nm, comparable to the mean free path of the material (150 nm) at room temperature, and therefore the transport between the two QPCs can be regarded as ballistic or quasi-ballistic. While electrons travel through the ballistic cavity of the TBJ, they do not lose their energies, which generates strong intrinsic nonlinearities in the TBJ electrical properties (For detailed analysis, see Ref. [2]). Figure 2 shows a typical result of measurements of the nonlinearity of the TBJ, where V_L and V_R are applied to the left and right branches, and the output from the central branch V_C is recorded. The measurements were made under static conditions, but similar “pyramid” characteristics are expected to be observed at frequencies up to GHz or THz [4].

GaAs based planar QWTs were manufactured by focus ion beam [5] or electron beam lithography in 1990s [6]. These planar QWTs showed good transistor characteristics. In planar QWTs, two in-plane gates and one quantum-wire conducting channel can be integrated by a single-step lithography, in contrast to traditional field-effect transistor architectures. Thus, for the realization of a given function, the planar QWT circuitry is simpler. For example, a logic NAND gate can be achieved with a single planar QWT [7]. Figure 3 is an AFM image of a planar QWT, where the source, drain, upper gate, and lower gate are indicated by S, D, UG and LG, respectively. Figure 4 shows the I-V characteristics of the device. The source is grounded and V_D is applied to the drain. The gate voltage of LG, V_G, is increased from -2 V to 5 V in steps of 0.5 V, and UG is floating. At each value of V_G, V_D is swept from 0 V to 5 V. In figure 4, the curve where V_G = 0 V is marked by thick line. Normally, a planar QWT is an “on” field-effect transistor. At negative gate voltage, the gating efficiency is better than that at positive V_G.

3. Single TBJ frequency mixer and phase detector

Based on the nonlinearity of TBJs, a number of nanoelectronic devices can be made [8]. In this section, we show that a single TBJ can serve as a frequency mixer or a phase detector [9], both are two essential elements in telecommunication analogue circuits. Figure 5 shows the properties of a TBJ mixer. Two AC sinusoidal signals with frequencies of f_1 = 9 kHz and f_2 = 10 kHz are sent into the left and right branches of a TBJ, respectively. The AC voltage output at the central branch is recorded by an oscilloscope. In figure 5, (a) is the measured output signal, whereas (b) is the expected result, both in time domain. (c) and (d) correspond to the same signal in (a) and (b), respectively, but transferred into the frequency domain. The frequency mixing effects, i.e., the sum and difference frequency signals at 19 kHz and 1 kHz, are well resolved. The recorded data are in agreement with the expected data extracted from figure 2, except that they show amplitude decay at high frequencies. This, however, is a high-frequency AC measurement problem in contemporary nanoelectronics rather than an intrinsic device problem [10].

As a special case of the mixer, where f_1 = f_2, the same device can also be employed as a phase detector. In this case, one measures the central branch DC voltage output instead of the AC output. The DC output
is proportional to the phase difference \( \Delta \phi \) between the two inputs. Figure 6 shows the \( V_C - \Delta \phi \) curves of a TBJ phase detector with the input signals of frequencies \( f_1 = f_2 = 1 \text{ MHz} \), where (a) and (b) represent the sine-wave input case, and (c) and (d) the square-wave case. Again, the left two curves are the measured data, whereas the right two curves the expected results. It is seen that for sine-wave inputs, the \( V_C - \Delta \phi \) curve is sine-like, and for square-wave inputs, the \( V_C - \Delta \phi \) curve is triangle-like. In the phase detector applications, only the DC output is needed. The AC measurement technological problem is thus bypassed, offering a feasible high frequency application.

4. RS flip-flop unit based on planar QWTs
RS flip-flop unit is an important sequential logic circuit in digital electronics. Figure 7 (a) is an AFM picture of the central part of a planar QWT-based RS flip-flop unit, together with some auxiliary elements. Two planar QWTs are coupled to each other through side gates. The input \( S \) (\( R \)) is connected to the lower (upper) in-plane gate of the upper (lower) QWT, as well as to the source of the lower (upper) QWT. The two drains are connected to the ground through two 200 k\( \Omega \) resistors and two voltage shift units (with \( U_1 = U_2 = 1.5 \text{ V} \)). The output of the RS flip-flop element \( Q \) ([\( \bar{Q} \)]) is recorded from the lower (upper) side gate of the lower (upper) planar QWT. The two outputs are also connected to the negative poles of the two voltage shift units as a feedback control. Figure 7 (b) shows the results of measurements of the device. The logic 1 (0) state of the input is 0 V (-0.3 V), whereas the output for logic 1 (0) is -0.04 V (\( \leq -1.2 \text{ V} \)). The results agree with the RS flip-flop logic truth table very well. The logic swing of the outputs is about 4 times as large as that of the inputs, indicating a good signal magnification function of the RS flip-flop unit.

5. RS flip-flop unit based on TBJs and planar QWTs
The nanoelectronic RS flip-flop unit can also be realized by another design, as shown in figure 8 (a). Two TBJs, with the branches being indicated by \( L \), \( R \), and \( C \) with subscripts, are capacitively coupled to each other. \( C_1 \) and \( C_2 \) stretch out toward the opposite directions to avoid cross-talking effects. The narrowest part of the left (right) branch of the lower (upper) TBJ can also be regarded as the conducting channel of the lower (upper) QWT. For instance, the channel of the upper QWT is the “neck” of \( R_2 \), and the two side gates are \( C_1 \) and \( G_1 \). The two inputs \( S \) and \( R \) are applied to \( L_1 \) and \( R_2 \), \( R_1 \) and \( L_2 \) are applied with 2.5 V. \( C_1 \) and \( C_2 \) are grounded through two voltage shift units (with \( U_1 = U_2 = 1.5 \text{ V} \)) and two 100 M\( \Omega \) resistors. The two outputs \( Q \) and \( \bar{Q} \) are recorded from the negative poles of the two voltage shift units. At the same time, they are connected to the lower and upper in-plane gates of the two QWTs as signal feedbacks. Figure 8 (b) is the logic properties of the RS flip-flop. The 1 (0) level of the input is defined as 0 V (-0.6 V). The logic 1 (0) of the output is \( \geq 0.4 \text{ V} \) (-1 V). The device also shows reproducible RS flip-flop functionalities. Furthermore, we have achieved large noise margins of 0.4 V in both high and low level inputs of this device, which is very important for further integration of circuits.
6. Summary

In conclusion, we have successfully realized novel room-temperature functional analogue and digital nanoelectronic circuits based on TBJs and planar QWTs. The properties of the single TBJ frequency mixer and phase detector are demonstrated, as a typical example of the TBJ-based analogue nanoelectronic circuitry. In digital nanoelectronics, first we fabricate a planar QWT-based RS flip-flop element, where large signal gain of 4 is achieved. Second, we fabricate an RS flip-flop by the integration of TBJs and planar QWTs, and large noise margins of 0.4 V are obtained in both high and low level inputs of the device. The results in this work indicate the potential applications of TBJs and planar QWTs in nanoelectronics.

References

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