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High Field Electron Transport in the Ballistic T-Branch Junction

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1. Introduction

Nanolithography has advanced to the point where it is now possible to fabricate electron devices with dimensions smaller than the electron mean free path at room temperature. This has led extensive research on seeking a room temperature ballistic device. Among such ballistic devices, the T-branch junction (TBJ) [1,2] is one of the promising candidates because of its advantages such as small capacitance, small area, and room temperature operation. In this paper, we focus on the high field transport in TBJ. Generally speaking, as the geometrical size of ballistic device shrinks, it is expected that the device performance is improved. However, at the same time, the electric field becomes more intense in smaller device, which could induce higher scattering rate and eventually diminish the ballistic effect. To realize a room temperature ballistic device, it is important to answer those questions by investigating a role of the high field transport in sub-micron ballistic devices.

2. The T-Branch Junction

The TBJ consists of a T-shape conductor that is typically made of two dimensional electron gas (2DEG) and Ohmic contacts at three stems. An SEM picture of our TBJ is shown in Fig. 1. Side stems (L and R) are used for signal input and the lower stem (C) is used for output in a typical operation mode. When a push-pull voltage is applied (V_L = -V_R = V), V_C is expected to be zero because of its symmetrical geometry. However, the actual measurements indicate that V_C becomes negative regardless of the sign of the input voltage. It has been known that the nonlinear characteristic can be used for performing a logic function [3] and amplifying a signal [4]. Also, thanks to its simple (no explicit gate and no highly doped region) and in-plane structure, TBJ has an extremely small capacitance or a short RC delay, which opens up a possibility of realizing a THz electron device.

The TBJs presented were fabricated from a modulation doped $In_{0.53}Ga_{0.47}As$ / $In_{0.52}Al_{0.48}As$ lattice-matched heterostructure on a semi-insulating InP substrate. The 2DEG is approximately 60 nm from the surface. Electron beam lithography and ion mill etching were performed to define the device geometry by mesa structure with 130 nm height. This was followed by the formation of alloyed Ni/Ge/Au ohmic contacts and the deposition of Ti/Au probe pads. In order to investigate the influence of ballistic transport on the nonlinear characteristic, TBJs with channel length (L) of 160 – 2000 nm were prepared and tested at between 295 K and 4.5 K so that the ratio of elastic mean-free-path (l_e) to L is altered. The l_e was calculated by $l_e = h\mu n^{1/2}/(2\pi)^{1/2}e$, where h is the plank constant, μ is the electron mobility, and n is the electron concentration. The l_e was found to be 120 nm at 295 K and 850 nm at 77 K from the Hall measurement.

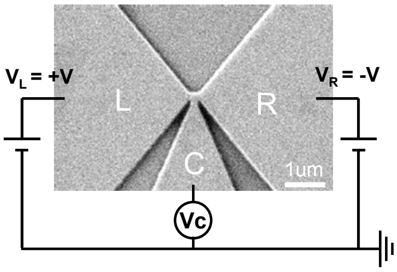

Fig.1 SEM image of T-branch junction. Push-pull voltage is applied to left and right electrodes (V_L= +V, V_R = -V) and voltage of central probe (V_c) is measured by high impedance voltmeter.

3. Strong Nonlinear Behavior at Large Voltage Regime

In Fig. 2, typical electrical responses of TBJ are shown. The two data in Fig. 2 are for two extremes; one is for the ballistic mode, in which l_e is much longer than L, and the other is for the diffusive mode. Interestingly, the two exhibit similar behavior as follows. At small voltage regime, the V_C has a quadratic dependence and I_{LR} increases linearly. Then at the large voltage regime, V_C becomes linear with nearly unity slope and I_{LR} saturates. The only obvious difference between the two data is the transition voltage between the two regimes.

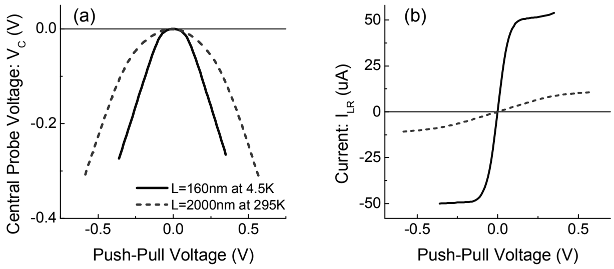

Fig.2 (a) V_C – V and (b) I_{LR} – V plots for ballistic and diffusive channel.

For more quantitative analysis, a derivation of V_C in Fig. 2 was performed (Fig. 3). This analysis clearly shows that (i) the derivative becomes $\mp$ 1 at the large voltage regime, which indicates that V_C is perfectly pinned to the voltage of either side stem with lower voltage, (ii) the derivative has a linear dependence at the small voltage regime, which means that V_C certainly has a quadratic dependence. The latter behavior is known as the nonlinear ballistic effect which has been studied both theoretically [1] and experimentally [2]. As is expected, the curvature of the parabolic shape is sensitive to the transport mode, and the parabola becomes more flat in diffusive channel (Fig. 2). Contrary to that, the unity slope behavior at the large voltage regime is insensitive to the transport mode and is seen in all experimental conditions. Thus, we attribute that to a non-ballistic effect. The V_c in this regime can be written as;

$$V_{C\_large} = -|V| + V_{onset}$$

A possible mechanism of this non-ballistic effect is the intervalley transfer [5,6]. InGaAs has several conduction band minima. In equilibrium condition, all electrons exist in the Γ-valley that is the lowest energy valley. However, once an applied electric field exceeds a threshold (E_{th}), the strong lateral field provides sufficient energy to make a transition from lower valley (Γ-valley) to the upper valleys (X or L-valley) along with an optical phonon scattering. Since the effective mass of the upper valleys is lower than that of the Γ-valley, a high field domain appears like the Gunn effect. The high field domain, formed near the anode, makes V_C pinned to the potential of the cathode and saturates I_{LR}. Those features are observed in Fig. 2. Furthermore, according to the Monte Carlo simulation in Ref. 6, the V_{onset} is about 0.15 V at 300 K for a TBJ with L = 750 nm, which consists with our experimental data. Therefore, it is concluded that the negative V_C with unity slope is caused by the intervalley transfer mechanism.

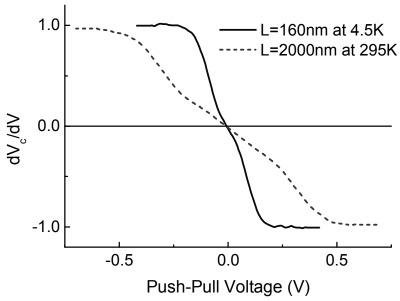

Fig.3 Derivative of V_C in Fig. 2

4. The Onset Voltage in the Ballistic Transport Mode

Finally, the role of ballistic transport in the intervalley transfer is discussed. Since the intervalley transfer is triggered by a scattering, it seems to be irrelevant to the ballistic transport. However, to be scattered into a higher valley, the electron has to gain a sufficient energy. In that process, the transport mode is important and gives rise to a difference. In Fig. 4, V_{onset} is shown with respect to L at different temperatures. In the diffusive mode (at 295 K and L > ~200 nm), the V_{onset} is proportional to L. This can be explained by the intervalley transfer being triggered at a constant E_{th}. According to the previous experiments [7], E_{th} is in the range from 2 kV/cm to 5 kV/cm for the long channel device ($L \gg l_e$), which is consistent with the E_{th} estimated from the slope of our data (~2.0 kV/cm). On the other hand, in the ballistic mode, the V_{onset} remains the same and is independent of L. This is clearly observed at 4.5 K, where all data points have almost same value of V_{onset}. This anomalous behavior has not been observed as far as we know. Although further modeling and verification are required, there is a qualitative explanation as follows; in the intervalley transfer mechanism, the electron has to acquire a sufficient amount of energy to make the transition to the upper valley. To obtain such energy, the electron needs a finite distance for acceleration, which is known as "dead space" in the Gunn effect because it prevents domain creation and limits the minimum device length. From an alternative perspective, the length is considered as a mean-free-path of intervalley transfer (l_i). Thus, once L becomes shorter than l_i, V_{onset} is not limited by narrow constriction anymore and becomes independent of L. One should note that l_i is comparable with l_e at 295 K. Moreover, temperature dependence of V_{onset} suggests that l_i correlates with l_e, and l_i becomes longer than 2 μm at 4.5 K.

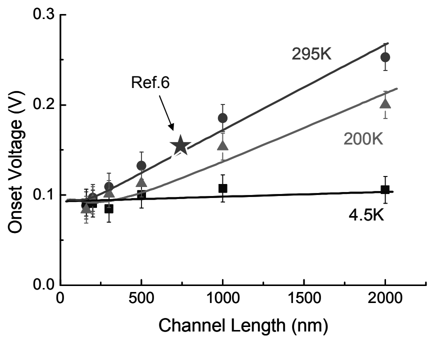

Fig.4 Channel length dependence of the onset voltage. Points represent experimental data, the star represents a datum of the Monte Carlo simulation in Ref. 6, and lines are just guides for eye.

5. Conclusions

It was found that two different mechanisms, nonlinear ballistic effect and intervalley transfer, are involved in the nonlinear characteristic of the TBJ. Under a large voltage, the intervalley transfer mechanism always dominates irrespective of transport mode. Finally, channel length and temperature dependence of the onset voltage indicates that the intervalley transfer in ballistic mode is triggered by a constant voltage, which is quite different from the high field effect in diffusive mode.

Acknowledgements

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