Nonlinear electron transport in InAs/AlGaSb three-terminal ballistic junctions

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Abstract. We have fabricated and characterized an InAs/AlGaSb three-terminal ballistic junction device. The fabricated device exhibited nonlinear electron transport properties because of ballistic motion of electrons in this structure that is comparable to the electron mean free path. When the left branch is biased to a finite voltage $V$ and the right to a voltage of $-V$ (push-pull fashion), negative voltages appeared at the floating central branch regardless of the polarity of the input voltages. In the case of the central branch grounded in push-pull fashion, the clear current rectification effect also observed in the current flow of the central branch at 4.2K to even at 300K.

1. Introduction

As one of low dimensional electron systems for future electron device, nanostructure devices so-called three-terminal ballistic junctions$^{[1-10]}$, such as T-shaped$^{[5,6,8,9,11]}$ and Y-shaped$^{[3,4,7]}$, are attractive for future electron devices. So far, in addition to theoretical predictions$^{[1,2]}$, several devices using three-terminal ballistic junctions have been reported such as a DC rectification device$^{[3,6,7,8]}$, a frequency mixer$^{[11]}$ and a fundamental constitutive device for logic circuits$^{[9]}$. These functions are mostly based on nonlinear electron transport properties generated by ballistic electrons supplied from the cathode electrode. As a usual nonlinear property due to ballistic electrons, the floating output voltage from the central branch always shows negative polarity if finite voltage $+V$ and $-V$ are applied to left and right branch of the symmetric three-terminal ballistic junction$^{[3-10]}$. InAs/AlGaSb heterostructures are hopeful for utilizing ballistic devices because of long electron mean free path, and useful from the compatibility with monolithic microwave integrated circuits (MMICs) with InAs-related HEMTs developed in recent$^{[12]}$. It is significant to investigate the basic properties of InAs-based ballistic devices for integration them into InAs-based MMICs. In this paper, we report on experimental results on the nonlinear electron transport properties in the InAs/AlGaSb three-terminal ballistic junction. Clear nonlinear behavior and rectification effects reflected ballistic nature of electrons in the InAs/AlGaSb device are shown.

2. Experimental

The epitaxial layer of the InAs/AlGaSb heterostructures was grown by solid source molecular beam epitaxy on a semi-insulating GaAs (100) substrate. The heterostructure consists of an doped 1.5 µm thick AlSb buffer layer, AlSb/GaSb superlattices, a 200 nm AlGaSb bottom barrier, an 8 nm AlSb barrier layer, a 15 nm InAs channel layer, a 15 nm AlGaSb upper barrier layer, and a 10 nm GaSb cap layer. The Hall effect measurements by the van der Pauw method showed the electron mobility of
19,900 cm$^2$/Vs at 300K and 65,300 cm$^2$/Vs at 77K. The corresponding sheet carrier densities showed ranging from $1.1 \times 10^{12}$ cm$^{-2}$ to $1.8 \times 10^{12}$ cm$^{-2}$. Estimated electron mean free paths with these parameters were 430 nm at 300K and 1.15 µm at 77K.

The branch pattern of the device was defined by electron beam lithography with ZEP-520A resist and wet chemical etching. The depth of the etched parts was about 60 nm. After these processes, a Hall bar structure was fabricated by photolithography. All regions except for the mesa of Hall bar structure were covered with SiO$_2$ insulator in order to prevent leakage current from flowing through the buffer layers. GaSb/AlGaSb upper layers were selectively etched by photore sist developer (MICROPOSIT MF-319) to obtain good ohmic contact. Finally, non-alloyed ohmic and bonding pad metals were directly deposited onto the InAs channel layer by thermal evaporation. An atomic force microscope image of the T-shaped three-terminal ballistic junction with the measurement configuration is shown in Fig. 1. The width of the left and the right branch is about 500 nm, and that of the central branch is about 250 nm.

3. Results and discussion

The voltages $V_L$ and $V_R$ are applied to the left and right branches, respectively. The output voltage $V_C$ at the central branch is detected. We measured output voltage $V_C$ by sweeping the $V_L$ from -1 to 1 V while keeping the $V_R$ constant. After the sweep of $V_L$, the $V_R$ was also changed from 1 to -1 V in steps of -0.1 V. Figure 2 shows the output voltage $V_C$ measured at various temperatures. As can be seen in Fig. 2, nonlinear characteristics and saturation of the output voltages $V_C$ were observed from 4.2K to 300K. Peculiarly, $V_C - V_L$ curves at 4.2K (Fig. 2 (a)) and 77K (Fig. 2 (b)) show strong saturation characteristics of $V_C$. Although saturation regime of $V_C$ observed for positive $V_L$ values at low temperatures disappeared, weak nonlinearity is still observed even at 300K. From the theoretical prediction based on the model using ballistic cavity\cite{1,2}, the output voltage from the central branch is expected to show diode like nonlinear characteristics by applying finite voltage to one of the two symmetric branches with the other branch grounded. Observed nonlinear characteristics agree with the theoretical prediction, that is, when the applied voltage to the right branch is grounded ($V_L = V$ and $V_R = 0$), the $V_C$ changes linearly for $V_L < 0$, and saturated for $V_L > 0$ V. Moreover, when the finite voltage

Figure 1. AFM image of an InAs/AlGaSb three-terminal ballistic junction that consisted of the left and the right horizontal branch and the central branch. The measurement configuration for $V_C - V_L$ characteristics has two voltage sources and one floating terminal connected to a voltmeter.

Figure 2. Output voltage $V_C$ versus applied voltage to the left branch $V_L$ for various voltages of $V_R$ measured at (a) 4.2K, (b) 77K and (c) 300K. $V_R$ was changed from 1.0 to -1.0 V by -0.1 V step for the curves from top to bottom.
is applied on the grounded branch, triode characteristics of $V_C$ are also predicted by Xu[2]. The results shown in Fig. 2 agree with the theoretical[2] and the experimental work[9] on triode characteristics.

In order to investigate the rectification effect in three-terminal ballistic junction, we can extract the $V_C$–$V_L$ characteristics biased in the push-pull fashion. Figure 3 shows extracted output voltage $V_C$ versus $V_L$ at 4.2K, 77K and 300K, respectively. This fashion means that $V_L$ and $V_R$ are applied same absolute value of $V$ in an opposite polarity. Each plot of Fig. 3 is extracted values corresponding to $V_C$ biased with the push-pull fashion. It is clearly seen that the device shown in Fig. 1 operates similarly to a four-terminal ballistic rectifier[13]. The negative voltages $V_C$ are obtained ranging from 4.2K to 300K with this configuration. As previous results show[3], the pronounced nonlinear effects and the rectification effects shown in Fig. 3 are related to the properties of the ballistic electron transport and to the geometric symmetry of the device. The clear rectifications and the larger negative voltage of $V_C$ are observed due to the longer mean free path at 77K and 4.2K. On the other hand, a weaker rectification is attributed to shorter mean free path at 300K.

Characterizing the rectification behavior on the changing of $V_C$, the switching parameter $\gamma = dV_C/dV_L$ can be expressed as a function of $V_L$ with the push-pull fashion. This parameter is defined for evaluating the ballistic switching mode[3]. Figure 4 shows the measured $\gamma$ for the different temperatures. The ballistic switching efficiency is found from the $\gamma$ at low biased region[3,7,10]. Therefore, it is expected that the switching degree $\gamma$ become steeper when the transport property of electrons is dominated by ballistic electrons[7]. The larger switching degree is observed at 77K and 4.2K as shown in Fig. 4 because of stronger ballistic nature. Previously, it has been reported that the $\gamma$ saturates constant value at higher applied voltage using push-pull fashion in Y-branch three-terminal ballistic junctions[3,7]. From Fig. 4, the absolute $\gamma$ value reaches a peak at around $V_L = \pm 0.5$ V, and decreases for higher $V_L$ especially at 77K and 4.2K. This means that the conductance of the branch connected to the positive voltage increased for $|V_L| > 0.5$ V resulting in a decrease in the rectification effect. It is likely that the increase in the conductance of the branch connected to positive voltage is caused by the excess carrier generation due to the impact ionization at this branch for $|V_L| > 0.5$ V.

Figure 5 shows the measurement configuration for investigating the dependence of the current flow through the central branch $I_c$ on the input voltage in the push-pull fashion and the $I_C$–$V_C$ characteristic. Input voltages $+V$ and $-V$ are applied at left and right branch with the push-pull fashion, and the central branch is grounded[3,6]. The $I_c$ was calculated by $I_c = I_R - I_L$, and was measured at 4.2, 77, and 300K. The $I_c$ shows positive values regardless of the input voltage polarity. Although the values of $I_R$ and $I_L$ were strongly temperature dependent, the resulting $I_c$ showed much less temperature dependence as shown in Fig. 5. These results mean that the current rectification effect is confirmed for each temperature.

**Figure 3.** Output voltage $V_C$ versus $V_L$ when $V_R = -V_L$.

**Figure 4.** Value of switching parameter $\gamma = dV_C/dV_L$ versus $V_L$ when $V_R = -V_L$.
4. Conclusion
In summary, we have fabricated and characterized an InAs/AlGaSb submicron three-terminal structure. This structure exhibited nonlinear electron transport properties from 4.2K to 300K because of ballistic properties of electrons. When dc input voltages are applied to the left and right branches in the push-pull fashion ($V_L$ and $V_R$), the voltage measured at the central branch $V_C$ showed obvious rectification properties with respect to $V_L$ from 4.2K to 300K. In addition, current rectification effects in the current flow through the central branch were observed with the central branch being grounded and input voltages in push-pull fashion. These clear nonlinear effects indicate that the InAs/AlGaSb three-terminal device is one of the attractive future applications utilizing ballistic electron transport properties.

[1] Xu H Q 2001 Appl. Phys. Lett. 78 2064
[2] Xu H Q 2002 Appl. Phys. Lett. 80 853
[3] Hiieke K and Ulfward 2000 Phys. Rev. B 62 16727
[4] Worschech L, Xu H Q, Forchel A and Samuelson L 2001 Appl. Phys. Lett. 79 3287
[5] Shorubalko I, Xu H Q, Maximov I, Omling P, Samuelson L and Seifert W 2001 Appl. Phys. Lett. 79 1384
[6] Shorubalko I, Xu H Q, Omling P and Samuelson L 2003 Appl. Phys. Lett. 83 2369
[7] Rashmi, Bednarz L, Hackens B, Farhi G, Bayot V and Huyen I 2005 Solid-State Comm. 134 217
[8] Wallin D, Shorubalko I, Xu H Q and Cappy A 2006 Appl. Phys. Lett. 89 092124
[9] Xu H Q, Wallin D, Maximov I, Omling P, Samuelson L and Seifert W 2004 IEEE Electron. Dev. Lett. 25 164
[10] Mateos J, Vasallo B G, Pardo D, González T, Gallo J, Bollaert S, Roelens Y and Cappy A 2003 IEEE Trans. on Electron Devices 50 1897
[11] Sun J, Wallin D, Brusheim P, Maximov I, Wang Z and Xu H Q 2007 Nanotechnology 18 195205
[12] Bergman J, Nagy G, Ikhsassi A and Brar B 2004 62th DRC. Conference Digest 243
[13] Koyama M, Takahashi H, Maemoto T, Sasa S and Inoue M 2007 AIP Conf. Proc. 893 577