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RESEARCH ARTICLE

Research on Carrier Correlation in Ballistic Transport Nano-MOSFETs

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Abstract:

Objective and Method:

In this paper,the experiment proved that shot noise is suppressed by Fermi and Coulomb interaction correlation. Meanwhile, the establishment of shot noise suppression factor (Fano) in ballistic transport nano-MOSFETs the Coulomb interaction correlation and the combination of the two effects are derived from separately considering the Fermi interaction correlation. And on this basis the variation of Fano with voltage, doping concentration and temperature are investigated.

Result:

The result we obtained which considered the combination of the two effects is in good agreement with experimental studies in the research papers, thus getting a theoretical explanation for the variation of the suppression factor with the bias voltage. Meanwhile, the suppression factor model is suitable for nano-MOSFET.

Keywords: Nano-MOSFET, Fano, Ballistic transport, Shot noise, Carrier transport, Quasi-ballistic.

1. INTRODUCTION

With the shortening of the channel length of MOSFET, the mechanism of the carrier has been changed as it passes through the channel. The carriers are drift-diffusive transport in long channel MOSFET, which is the result of a large number of carriers scattering in the field of electric field, thus the current noise is mainly thermal noise [1]. When the channel length is in the range of sub 100 nm, carrier transport mechanism shifts from drift diffusive to quasi-ballistic or even to ballistic transport (Quasi-ballistic transport means less carrier scattering times; ballistic transport is limiting case that the carrier shot noise [2 - 9]. The research has demonstrated the role of the Fermi and Coulomb correlations in the nano-MOSFET, and the simulation has been carried out [6, 7, 10]. The Fermi correlation effects carrier injection in the contact side, and the higher carriers degenerate, the stronger the suppression of Fermi on the shot noise;the Coulomb correlation can change carriers, and the stronger the space charge effect, the stronger the suppression of Coulomb on the shot noise .

Although it can be concluded from the experimental results and the simulation results that shot noise is suppressed in nano-MOSFET [3, 4, 6, 11], and the Fano is closely related to the device structure parameters and working parameters, there are still no suppression mechanism and shot noise suppression strength in-depth theoretical study. The research showed that noise expression in nano-MOSFET, and considering the existence of Fermi and Coulomb at the same time, only the Fermi or Coulomb interaction, or neither with simple analysis [7, 10]; The research established the total suppression factor formula of shot noise in ballistic MOSFET, with a simple explain and discussion on the

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relationship between the suppression factor and the gate voltage, but the formula for Coulomb and Fermi suppression was not analyzed respectively [6, 7, 10, 12 - 14]. At present, there is no comprehensive analysis of the carrier correlation.

In this paper, firstly, the experimental results showed that the shot noise is affected by the Fermi and Coulomb interaction correlation. Then, Fano models were established with theoretical analysis of the Fermi and the Coulomb correlation. The suppression of shot noise in different situations is discussed with the variation of the bias voltage, doping concentration and temperature. Finally, the suppression results are compared with the experimental results the macroscopic shot noise suppression and the existing suppression of shot noise in the ballistic transport MOSFET.

2. EXPERIMENTAL

Select the threshold voltage of 90nm n-MOSFET device was 0.7V, the width of the device(W) is 2×10^{-6}m, the thickness of the oxide layer is 1×10^{-9}m, the source and drain doping concentration(N_{SD}) is 1×10^{26}m^{-3},and the noise power spectrum(S) of the device was tested under low temperature. The device works in the sub-threshold region, which is the gate voltage (V_{GS}) is 0.25V. The variation of S with source-drain voltage (V_{DS}) was shown in Fig. (**1**). Then, the device works in the linear region and saturation region, which is V_{GS} is 1.2V, as shown in Fig. (**2**), the S changed with V_{DS}. As shown in figures, when the V_{DS} is small,S is not obvious; and V_{DS} increases, we can hear shot noise clearly, this is because the electric field increases in the channel, and lead to the barrier decreases, which means shot noise was suppressed by Fermi and Coulomb interaction correlation.

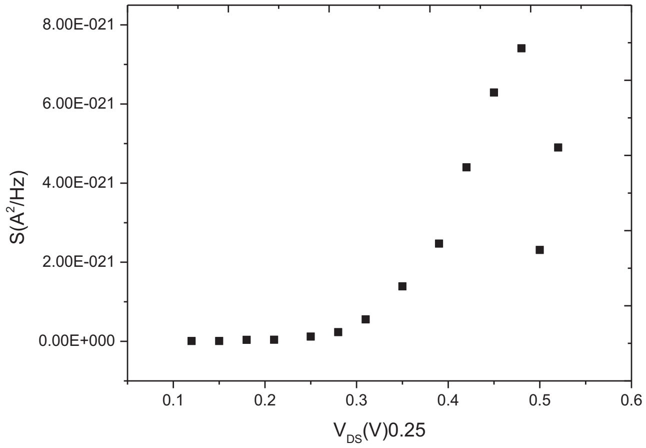

Fig. (1). The variation of S with V_{DS}.

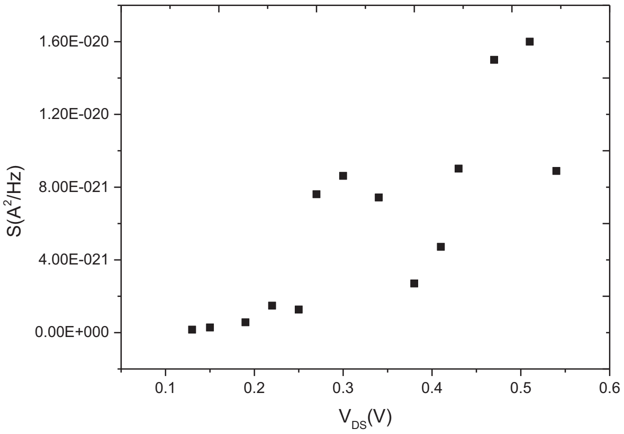

Fig. (2). The variation of S with V_{DS}.

3. SHOT NOISE SUPPRESSION FACTOR MODEL

The leakage current fluctuation is the common result of the Fermi effect and potential fluctuations, which leads to the suppression of shot noise. Based on the reference [7], Fano is derived in ballistic transport of nano-MOSFET. Considering the minimum sideband has been occupied, in order to simplify the formula, the following notation of 《》 is defined:

$$\langle\langle h\rangle\rangle = 2\int_0^\infty dE \cdot N_D h. \tag{1}$$

Where, *h* is function of kinetic energy in transport direction E. Here, N_D is the electron density in the subband. The electron concentration per unit area can be expressed as:

$$n_D = \langle\langle f_S(E+E_M) + f_D(E+E_M)\rangle\rangle. \tag{2}$$

Where, $f_S(E)$ and $f_D(E)$ are the Fermi Dirac occupation factors. We assume that the fluctuations of the propagating states occupation factor affect have a direct impact on n_D through electrostatic effect on E_M. From (2), we can derive:

$$\delta n_D = \langle\langle \delta f_s + \delta f_D\rangle\rangle + \delta E_M \left\langle\left\langle \frac{\partial f_s}{\partial E} + \frac{\partial f_D}{\partial E}\right\rangle\right\rangle. \tag{3}$$

The gate capacitance per unit area C_G was used to simplify the approximation of total electrostatic effects, thus the relationship between the electron density and the maximum barrier value of the side band can be expressed as:

$$\delta E_M = q^2 \delta n_D / C_G. \tag{4}$$

From formula (3) and (4), it is concluded that

$$\delta E_M = \frac{q^2\langle\langle \delta f_S + \delta f_D\rangle\rangle}{C_G + C_{QS} + C_{QD}}. \tag{5}$$

Where,

$$C_{QS} = q^2\langle\langle \partial f_S/\partial E\rangle\rangle. \tag{6}$$

$$C_{QD} = q^2\langle\langle \partial f_D/\partial E\rangle\rangle. \tag{7}$$

When the side band barrier is maximum, the ballistic current density I_B at the top of barrier is expressed as:

$$I_B = q\langle\langle \upsilon[f_S(E+E_M) - f_D(E+E_M)]\rangle\rangle. \tag{8}$$

As can be seen from the above formula, the fluctuations of f_s , f_D and E_M have direct impacts on the Ballistic current.Considering the far from equilibrium case, in which f_D<<1, thus f_D can be discarded.

$$\delta I_B = q\left\langle\left\langle \upsilon\delta f_s + \upsilon\delta E_M \frac{\delta f_s}{\partial E}\right\rangle\right\rangle. \tag{9}$$

From formula (5) and (9), it is concluded that

$$\delta I_B / q = \left\langle\left\langle \upsilon\left(1 - \frac{\bar{\upsilon}_S C_{QS}}{C_G + C_{QS}}\frac{1}{v}\right)\delta f_s\right\rangle\right\rangle. \tag{10}$$

where $\overline{\upsilon_s}$ is a weighted mean of the velocity:

$$\bar{\upsilon}_S C_{QS} = -q^2\left\langle\left\langle \upsilon\frac{\partial f_s}{\partial E_{FS}}\right\rangle\right\rangle. \tag{11}$$

Current is the sum of the current pulses induced by all charged q, therefore $\overline{\delta f_s^2}=f_S(1-f_S)$, and the occupation factor of different modes are not related. So under Fermi and Coulomb interaction correlation, the Fano is

$$F=\frac{S}{2qI_B}=\frac{\left\langle\left\langle \upsilon\left(1-\frac{\bar{\upsilon}_S C_{QS}}{C_G+C_{QS}}\frac{1}{\upsilon}\right)^2 f_S(1-f_S)\right\rangle\right\rangle}{\langle\langle \upsilon f_S\rangle\rangle}. \tag{12}$$

Where, $f_s\,(1-f_s)=f_s-f_s^2$ is Fermi interaction. When $f_s<<1$, the small amount of high-end can be ignored, hence the formula mainly expresses Coulomb interaction correlation. Fano of the Coulomb interaction can be expressed as:

$$F_C=\frac{\left\langle\left\langle \upsilon\left(1-\frac{\bar{\upsilon}_S C_{QS}}{C_G+C_{QS}}\frac{1}{\upsilon}\right)^2 f_S\right\rangle\right\rangle}{\langle\langle \upsilon f_S\rangle\rangle}. \tag{13}$$

where, $\left(1-\frac{\bar{\upsilon}_S C_{QS}}{\upsilon\left(C_G+C_{QS}\right)}\right)^2$ is Coulomb interaction. When $\left(1-\frac{\bar{\upsilon}_S C_{QS}}{\upsilon\left(C_G+C_{QS}\right)}\right)^2=1$, the Fano of the Fermi interaction correlation can be expressed as:

$$F_F=\frac{\langle\langle \upsilon f_S(1-f_S)\rangle\rangle}{\langle\langle \upsilon f_S\rangle\rangle}. \tag{14}$$

It can be seen from the derivation of the formula that in order to get each Fano in ballistic nano- MOSFET, the top barrier energy E_M should also be obtained. The gate voltage is the sum of the surface potential and the voltage drop across the oxide in ballistic transport nano-MOSFET.

$$V'_{GS-B}=\psi_S-Q/C_{ox}. \tag{15}$$

Where $V'_{GS-B}=V_{GS-B}-V_{FB-B}$, $V_{FB-B}=V_T-(4\varepsilon_0\,\varepsilon_S N_A\Phi_F)^{1/2}/C_{Ox}-2\Phi_F$ is the flat-band voltage, C_{Ox} is the oxide capacitance per unit area, and $\Phi_F=(kT/q)\ln(N_A/n_i)$, N_A is channel doping concentration, n_i is the intrinsic carrier density. V_{GS-B} is the gate voltage of ballistic transport MOSFET; Ψ_S is the work function; Q is the charge at the top of barrier [15]. Eq. (15) can be deformed to:

$$V'_{GS-B}=-E_M/q+qn_S/C_{ox}. \tag{16}$$

E_M and V'_{GS-B}, Q are linked in formula(16). The carrier energy at the top barrier is generated by the positive emission rate of carriers in the source region and the negative emission rate of carrier in the drain region. So the top the barrier charge is also related to the top barrier potential as

$$n_S=\frac{N_D}{2}\left\{\exp\left[\frac{(E_F-E_M)}{kT}\right]+\exp\left[\frac{(E_F-qV_{DS}-E_M)}{kT}\right]\right\}. \tag{17}$$

where, $N_D=\sqrt{2m^*}/\pi\hbar$. is the effective density of states, E_F is the Femi energy. For a given gate and drain bias, Eq. (16) and (17) define a nonlinear equation for $n_S\,(V'_{GS-B}, V_{DS})$. Fig. (**3**) shows the relationship between the gate voltage with top barrier potential. It can be seen from the figure that with the increase of the gate voltage, the top barrier energy decreases.

4. THE ANALYSIS OF MOEEL RESULTS

Under the Fermi interaction correlation, the Coulomb interaction correlation and the combination of the two effects, the Fano with bias voltage, doping concentration and temperature are studied separately. The channel length of the MOSFET chosen was 90nm, V_{DS} is 0.8 V , V_{GS} is 0.4V, temperature (T) is 300K, the source and drain doping concentration (N_{DS}) is 1×10^{26}m^{-3}.

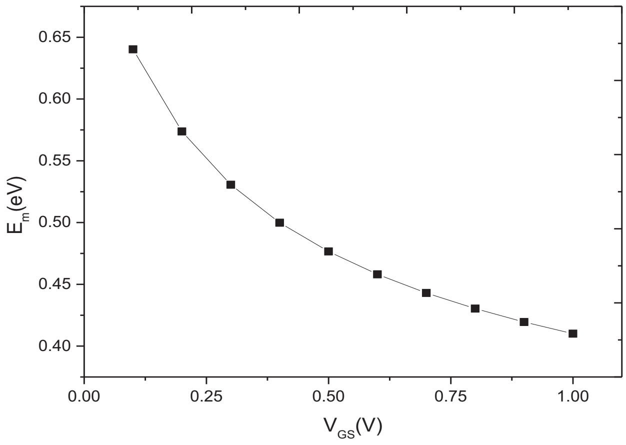

Fig. (3). The variation of E_M with V_{GS}.

4.1. Analyze the Effect of Voltage on Fano

The variation of Fano with V_{DS} was researched under the interaction of the Fermi interaction correlation, the Coulomb interaction correlation and the combination of the two effects. As shown in Fig. (**4**),it can be seen that each Fano decreases with the increase of source-drain voltage, but the change is not very obvious, and the total suppression(F) is stronger than Fermi (F_F)and Coulomb(F_C) alone. Experiment figure showed that when V_{DS}, the total shot noise suppression factor changed slightly the research papers [5],which is consistent with the changing trend of our theoretical results, and the theoretical explanation of the experimental results is also given.

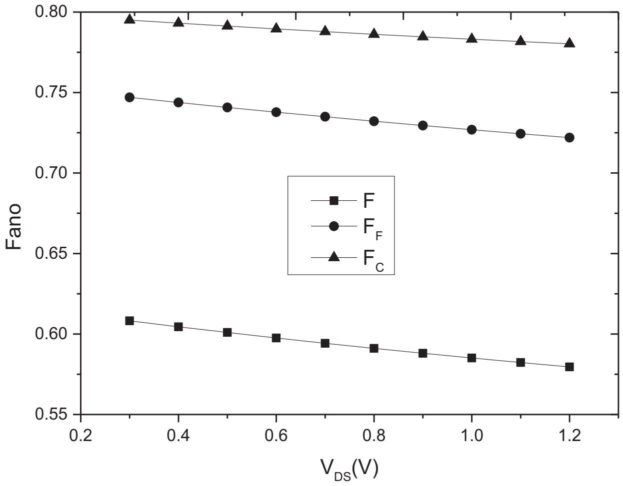

Fig. (4). The variation of Fano with V_{DS}.

The variation of Fano with V_{GS} is shown in Fig. (**5**). As the gate voltage increases, the longitudinal electric field increases, resulting in the increase of carrier surface scattering, the device transport deviates from the ballistic limit; while the electrons increase in inversion layer, and the carrier degeneracy increases, thereby enhancing the Fermi correlation to shot noise suppression [16, 17]. On the other hand, with the increase of the gate voltage,the channel barrier height reduces, the number of carriers increase, thus increasing the number of carrier inelastic scattering and the Coulomb correlation [18, 19], leading to the suppression of shot noise. The model not only follows the shot noise suppression in mesoscopic conductors, but also the experimental trend of total suppression factor with the gate voltage [5].

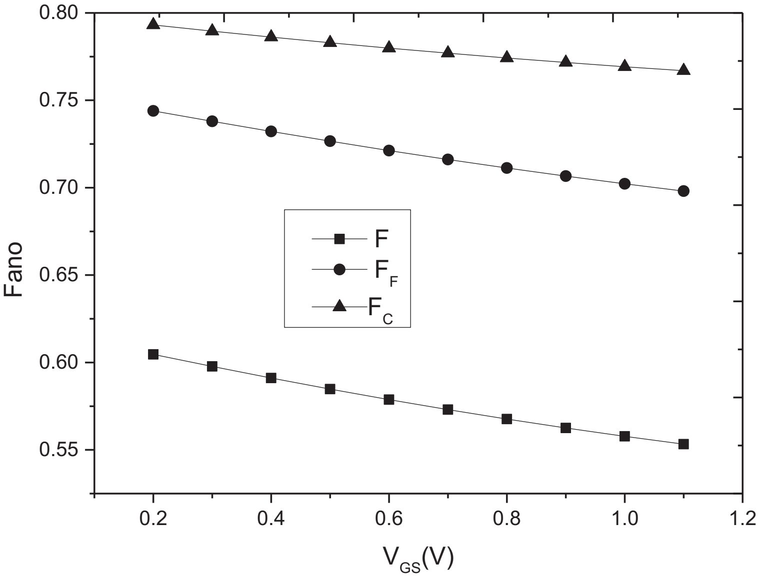

Fig. (5). The variation of Fano with V_{GS}.

4.2. Analyze the Effect of *T* and V_{DS} on Fano

The increase in temperature will stop shot noise becoming the main component of noise, because the noise suppression is enhanced by temperature, which is consistent with our model. The variation of each Fano with temperature is shown in Fig. (**6**). As shown in figure, the Fano decreases with the increase in T, and which is consistent with the conclusions in the research papers [3]. F_F and F_C decrease with the increase in *T* in the range of 150-300K, where the channel carrier scattering is mainly acoustic wave scattering and optical wave scattering, both scattering probability of which decreases with temperature. So with temperature increase, the number of phonon scattering increases, the average number of phonons increases, leading to the enhancement of shot noise suppression [3, 20 - 22]. And above 300K, Fano increases with temperature,this is because of the high temperature, the device transportation is changed from ballistic to drift-diffusion,and the device is mainly thermal noise.

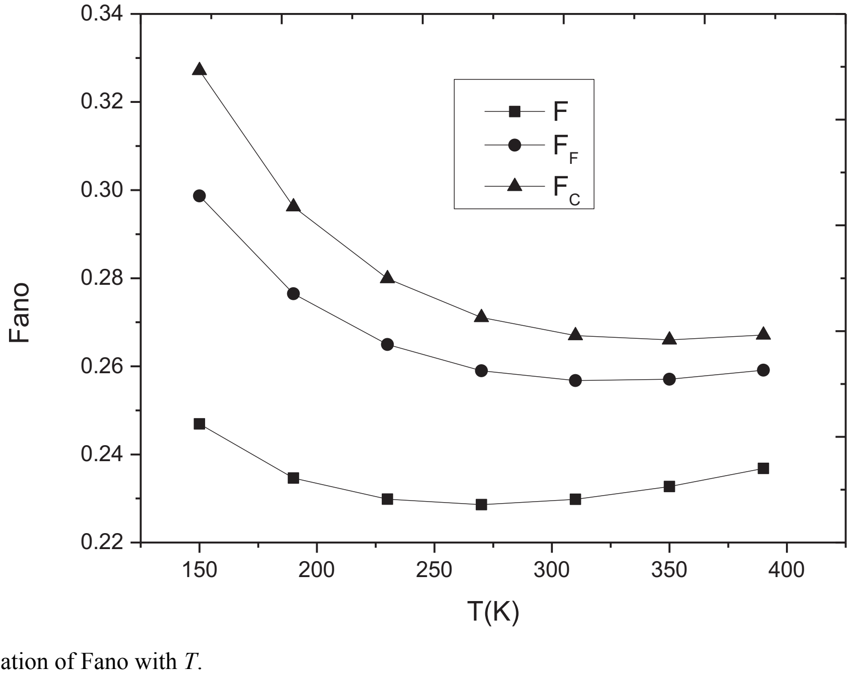

Fig. (6). The variation of Fano with *T*.

The variation of Fano with N_{DS} is shown in Fig. (**7**). With N_{DS} increases, each Fano decreases. The higher doping concentration in the source region, and the stronger shot noise are suppressed, and F is stronger than F_F and Coulomb F_C separately. The increase in doping concentration increases the carrier degeneracy, thus enhancing Fermi correlations. Meanwhile enhancing the space charge effect, increasing the Coulomb interaction correlation also increased [4, 16, 17, 23].

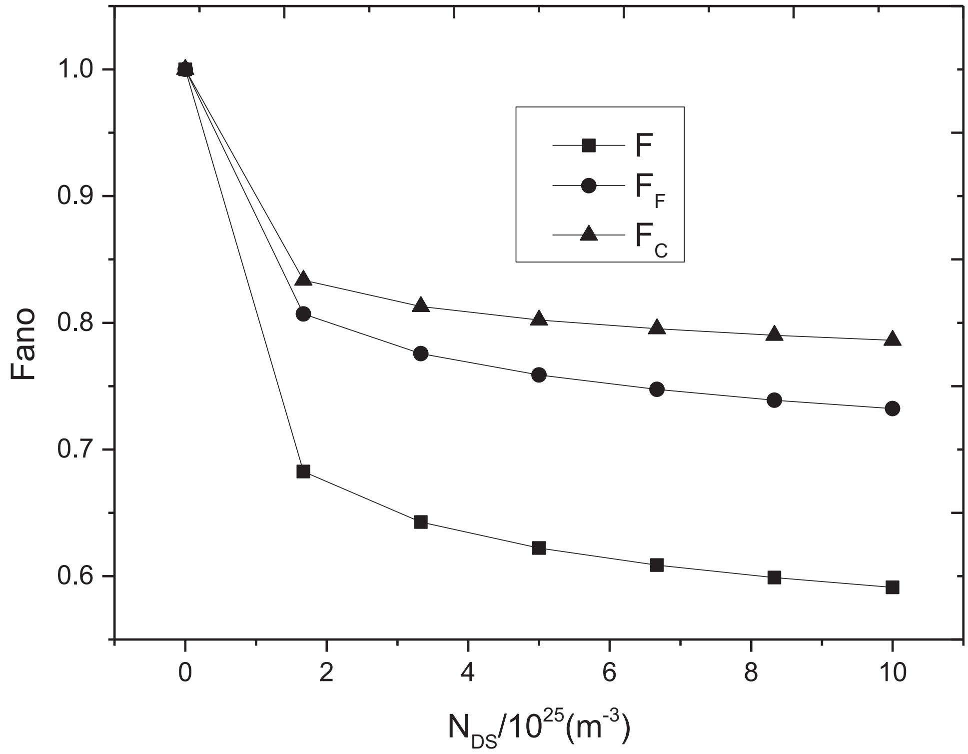

Fig. (7). The variation of Fano with N_{DS}.

CONCLUSION

In this paper,the experimental proved that shot noise is suppressed by Fermi and Coulomb interaction correlation in ballistic transport nano-MOSFET, and the expressions of Fano were derived with considering the Fermi interaction correlation the Coulomb interaction correlation and the combination of the two effects, respectively. The variation of each Fano with V_{DS}, V_{GS}, T, and N_{DS} was studied respectively. Experimental results showed that the variation of F with V_{DS} in ballistic nano-MOSFET was explained theoretically. The results showed that Fano decreases with increases in the voltage, the doping concentration and temperature.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No Animals/Humans were used for studies that are base of this research.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The author declares no conflict of interest, financial or otherwise.

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