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Experimental Investigations on Ballistic Transport in Multi-Bridged Channel Field Effect Transistors (MBCFETs)

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1. Introduction

Recently, to demonstrate a completely new concept of 3-dimensional (3D) transistor, multi bridged channel MOSFETs (MBCFET) have been fabricated successfully [1]. This device is immune to short channel effect thnaks to effective channel length increase, and it has high current drivability obtained from multiple channels.

The channel of the MBCFET is epitaxially grown high quality silicon and its size becomes comparable to the mean free path of the carrier. In such a regime, there is a possibility that the carrier can travel without scattering from source to drain electrode. In that case, the carrier transport mechanism changes from diffusive to ballistic transport.

There have been a lot of studies on the ballistic transport in single wall carbon nanotubes [2]-[4], whereas only a few papers have reported on the ballistic transport in 3D silicon devices [5]-[6]. In this paper, we present the experimental evidences of ballistic transport in MBCFET by investigating the device characteristics as a function of the gate length (L) ranging from 48 nm to 500 nm and as a function of temperature (T) ranging from 300 K to 4 K.

2. Results and Discussion

Fig. 1 (a) shows schematic diagram of MBCFET and Fig. 1 (b) shows cross-sectional SEM image of fabricated device. The electron channel is formed on both sides of the gates and we can obtain multiple parallel channels when we increase the number of embedded gates. We have investigated the electrical characteristics taken from seven devices with gate length (L) ranging from 48 to 500 nm, gate width (W) of 60nm and gate thickness of 20 nm.

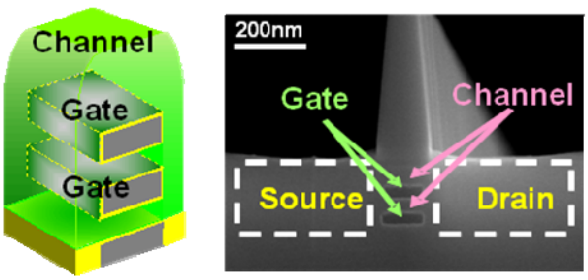

Figure 1. (a) Schematic diagram of the MBCFET fabricated using standard CMOS processes. (b) Cross-sectional SEM image.

We fit the saturation current I_{Dsat} with a power law, $I_{Dsat} \sim (V_G - V_T)^n$ from various devices, and Fig 2 (a) shows the fitted power (n) as a function of L. We find that n saturates the value of 1.3 in the sub-70 nm regime suggesting that, in this regime, the carrier transport mechanism in the channel was not completely dominated by the drift diffusion but by another transport mechanism [7].

Generally, in the drift-diffusion transport model, the resistance ($R_{Drift\text{-}Diffution}$) is given by

$$R_{Drift-Diffusion} = \frac{1}{nq\mu}\frac{L}{A} \qquad (1)$$

where q, μ, A , and n are the electron charge, mobility, cross-sectional area of the inversion layer, and electron density. On the other hand, in the ballistic transport model, the resistance $R_{Ballistic}$ is determined by

$$R_{Ballistic} = \left[\frac{2q^2}{h}N\right]^{-1} \qquad (2)$$

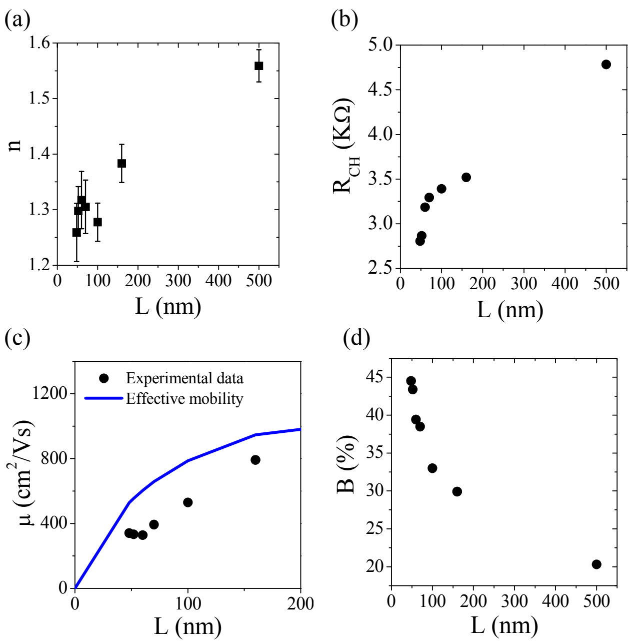

Fig. 2. (a) Extracted n as a function of L. (b) Extracted R_{CH} as a function of L. (c) Extracted μ as a function of L, (d) Extracted B as a function of L.

where h, and N are Planck constant, and the number of transverse modes propagating through the channel [8].

Fig 2 (b) shows the channel resistance (R_{CH}) as a function of L. We find that R_{CH} monotonously decreases with the decrease of L and saturates when L < 52 nm. The monotonous decrease of R_{CH} with the decrease of L indicates the drift-diffusion transport mechanism is dominant when L > 52 nm (Eq. (1)). No length dependence (saturation) of R_{CH} observed in the sub-52 nm regime can be interpreted as the existence of ballistic transport (Eq. (2)) in this regime.

Fig 2 (c) shows the extracted mobility (μ) as a function of L. The mobility decreases with the decrease of L. It can be explained by M. S. Shur's ballistic mobility model given by the Mathiessen's rule [9].

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_{ballistic}} + \frac{1}{\mu_o} \qquad (3)$$

Here, μ_{eff} is the effective mobility, $\mu_{ballistic}$ is the ballistic mobility given by $\mu_{ballistic} = 2qL/\pi m v_{th}$, μ_0 is the electron mobility in a long sample. The symbol m is the effective mass, and $v_{th} = (8kT/\pi m)^{1/2}$. The extracted μ in Fig. (c) shows a similar behavior with μ_{eff} in Eq. (3) (blue line in the figure). The reduction at small L regime is due to the decrease of $\mu_{ballistic}$.

The ballistic efficiency (B) which means the probability for electrons to be ballistic in the channel can be extracted by temperature dependent current (I) – voltage (V) characteristics [10]. We can obtain B as follows.

$$B = \frac{1 - r_{sat}}{1 + r_{sat}} \qquad (4)$$

where $r_{sat} = 1/(1 + \lambda_0/l_0)$, $\lambda_0/l_0 = 4/(0.5 - (\alpha + \eta)/(V_G - V_T)\ T) - 2$, $\alpha = \Delta I_{Dsat}/(I_{Dsat}\Delta T)$, $\eta = \Delta V_T/\Delta T$. The symbols r_{sat}, λ_0, l_0, α, η, are the backscattering ratio, mean free path, critical length, T dependence of I_{Dsat}, and T dependence of V_T, respectively. Fig. 2(d) shows the extracted B as a function of L. We observe remarkable increase of B when L < 52 nm. This is due to the decrease of r_{sat} and gate induced electric field increase as the L scales down. The value of B is small comparing with other devices [6], because enhanced surface roughness scattering is expected in our devices due to the increased channel length of our device.

Fig. 3(a) and 3(b) shows measured R_{CH} –T and n –T characteristics taken from the device with L = 100 nm in the T range from 300 to 4 K. When the temperature of the device decreases, the phonon scattering is reduced, and the chance of ballistic transport is increased. Therefore, it is expected that there is a cross-over from the drift-diffusion to ballistic transport in our MBCFETs. The value of R_{CH} and n decreases as temperature decreases until T > 50 K and saturates when T < 35 K. This transition indicates transport mechanism has completely changed from drift-diffusion to ballistic transport.

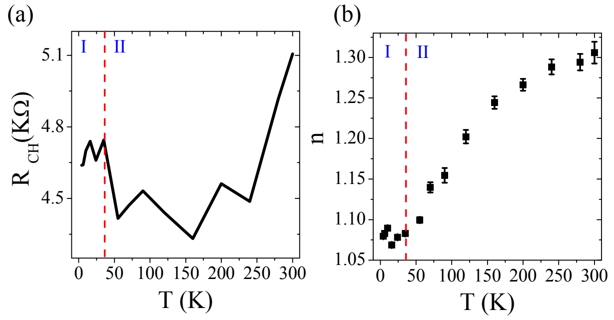

Fig. 3. (a) Extracted R_{CH} as a function of T. (b) Extracted n as a function of T. Ballistic and drift-diffusion transport regime are denoted by I and II

3. Conclusion

We present the electrical characteristics of MBCFETs with L ranging from 48 nm to 500 nm. The temperature dependence characteristics of the device with L = 100 nm also is shown in the range from 300 K to 4 K. We have observed the saturation of n and R_{CH} when L < 52 nm due to rapid increase of B. We have also observed the decrease of μ in the same length range. All these data are consistent with the crossover from the drift-diffusion to ballistic transport in L. The T-dependence of n and R_{CH} also shows a similar crossover in T, exhibiting the saturation when T < 35 K.

Acknowledgements

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References

[1] S.-Y. Lee, S.-M. Kim, E.-J. Yoon, C.-W. Oh, I. Chung, D. Park, and K. Kim, IEEE Trans. Nanotech. **2** (2003) 253.

[2] P. McEuen, M. S. Fuhrer, and H. Park, IEEE Trans. Nanotech. **1** (2002) 78.

[3] A. Javey, J. Guo, Q. Wang, M. Lundstrom, and H. Dai, Nature, **424** (2003) 654.

[4] J. Wang and J.-S. Wang, Appl. Phys. Lett. **88** (2006) 111909-1.

[5] K. H. Cho, K. H. Yeo, Y. Y. Yeoh, S. D. Suk, M. Li, J. M. Lee, M.-S. Kim, D.-W. Kim, D. Park, B. H. Hong, Y. C. Jung, and S. W. Hwang, Appl. Phys. Lett. **92**, (2008) 052102-1.

[6] R. Wang, R. Huang, L. Zhang, H. Liu, D.-W. Kim, D. Park, and Y. Wang, Appl. Phys. Lett. 93 (2008) 083513-1

[7] K. Natori, J. Appl. Phys. **76** (1994) 4879.

[8] M. J. Gilbert, R. Akis, and D. K. Ferry, J. Appl. Phys. **98** (2005) 094303-1.

[9] M. S. Shur, IEEE Electron Devices Lett. **23** (2002) 511.

[10] M.-J. Chen, H.-T. Huang, K.-C. Huang, P.-N. Chen, C.-S. Chang, and C. H. Diaz,, *Extended Abstracts in 2002 IEDM Tech. Dig.*(2002) 39.