Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 369-372 **C-8-5**

Novel Transport Characteristics of One-Dimensional Quantum Subbands in Si-MOSFET's

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A novel quantum Si-MOSFET device with controlled one-dimensional subbands is proposed. The devices have dual layer gates fabricated by electron beam lithography. The lower narrow gate produces the quantum conductive channel where one-dimensional subbands are formed. Making the small part of the channel narrower by field effect, the upper gate can modulate the transport characteristics. At 4.2K, the observed oscillatory structures of transconductance based on one-dimensional subbands are changed by the upper gate.

Introduction

Quantum devices which utilize the wave nature of electrons have been extensively investigated, since they are expected to yield new transport properties as functional devices. The remarkable progress of fabrication technology enables us to build devices with dimensions of less than 0.1μm, where various quantum effects appear at low temperatures. In a quantum wire of Si-MOSFET, the lateral confinement of electrons in the inversion layer leads to novel phenomena such as conductance fluctuations due to interference [1] and resonant tunneling [2] and conductance oscillations due to the quantization into one-dimensional subbands [3], [4].

This paper proposes a new Si quantum device in which the intervals of the quantized energy levels of the one-dimensional electron system are controlled by dual layer gates resulting in the modulation of transport characteristics. The experimental results at low temperature are also presented.

Device structure and operating principle

The device structure is shown schematically in Figure 1. The source and drain are formed by n^+ regions on a p^--Si substrate. The two layers of poly-Si-gates are fabricated by electron beam lithography. The widths of the gates varies from 0.1μm to 1μm and the channel length is approximately 2μm.

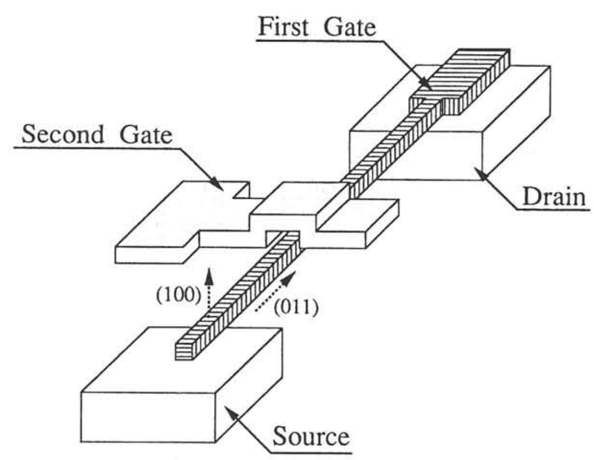

Fig. 1 Device structure.

The first gate, with a 10nm gate oxide layer, forms the narrow conductive channel at the substrate interface and changes the electron density and thus the Fermi energy as well. Since the channel width is approximately 0.1μm, the electron motion is

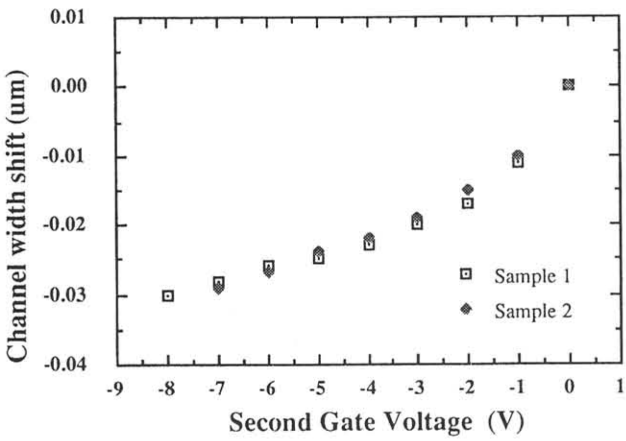

Fig. 2 Channel width shift vs. second gate voltage.

restricted to the direction parallel to the channel and hence one-dimensional subbands are formed. The second gate, which is insulated by a 50nm oxide layer from the first gate, can make the channel width under it narrower by suppressing the inversion of the substrate and causes the quantized energy level intervals to increase. As the second gate covers only a part of the first gate, the injected electrons from the source whose energies are quantized due to the one-dimensional confinement are modulated when they pass under the second gate region because the quantized energy levels under the second gate differ with those under the first gate only.

Supposing that the electron density is a function of only the first gate voltage V_{fg} and the effective channel width W is changed by the second gate voltage V_{sg}, the drain current I_d in the linear region can be represented as $I_d \propto V_d(V_{fg}-V_{th})W/L$. Here, V_d, V_{th} and L are the drain voltage, the threshold voltage and the effective channel length, respectively. With this equation, the channel width is estimated from the first gate voltage dependence of the drain current [4]. The channel width shift is shown as a function of the second gate voltage at room temperature for two different devices in Figure 2. The second gate effect is clearly seen, and drain current modulation by the second gate voltage is expected.

Results and discussion

Transconductances G_m ($= \partial I_d / \partial V_{fg}$) were measured with an AC lock-in amplifier at several temperatures with second gate voltage as a parameter. Figure 3 shows the results at room temperature and 77K. The widths of the first and second gate are 0.13µm and 0.55µm respectively. At temperatures higher than 77K, there is no fine structure seen in transconductances.

Figure 4 represents the results at 4.2K of the sample shown in Figure 3. The drain voltage was 10meV. The oscillatory behavior of transconductance is clearly observed. Figure 5 plots the peak positions of the transconductance in Figure 4 as a function of V_{fg} and V_{sg}. The level intervals of the peaks are nearly constant at small absolute values of V_{sg}, which indicates that the potential profile in the channel is like a harmonic-oscillator rather than a square well. However, when a square-well potential is assumed for simplicity, the lowest subband separation ΔE is calculated to be 0.3meV for the device in Figure 4 based on the equation $\Delta E = 3h^{2}/8m^{*2}W^{2}$,where

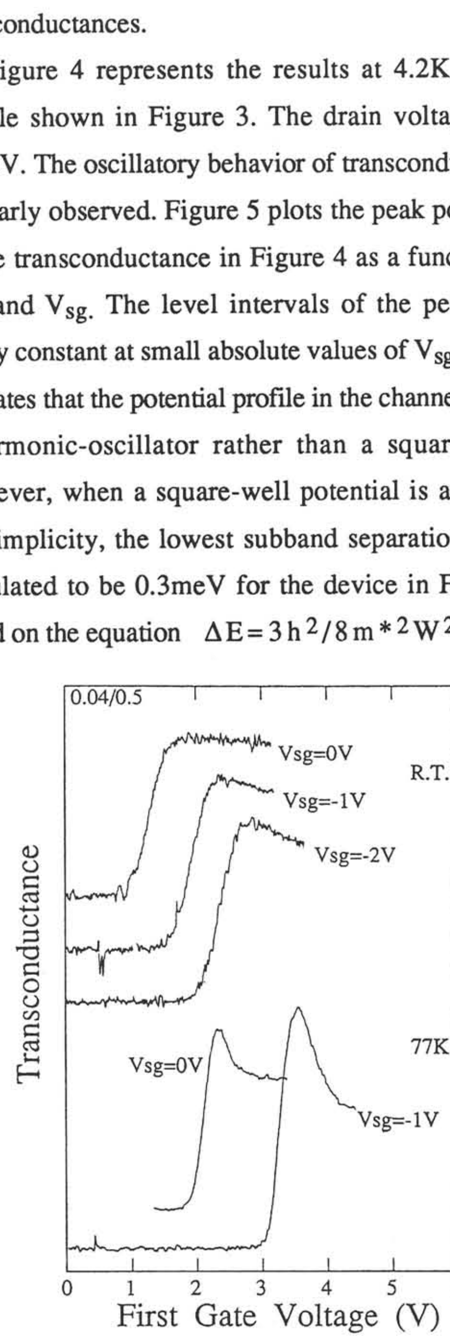

Fig. 3 Transconductance at 77K and room temperature of the device whose first and second gate widths are 0.13µm and 0.55µm.

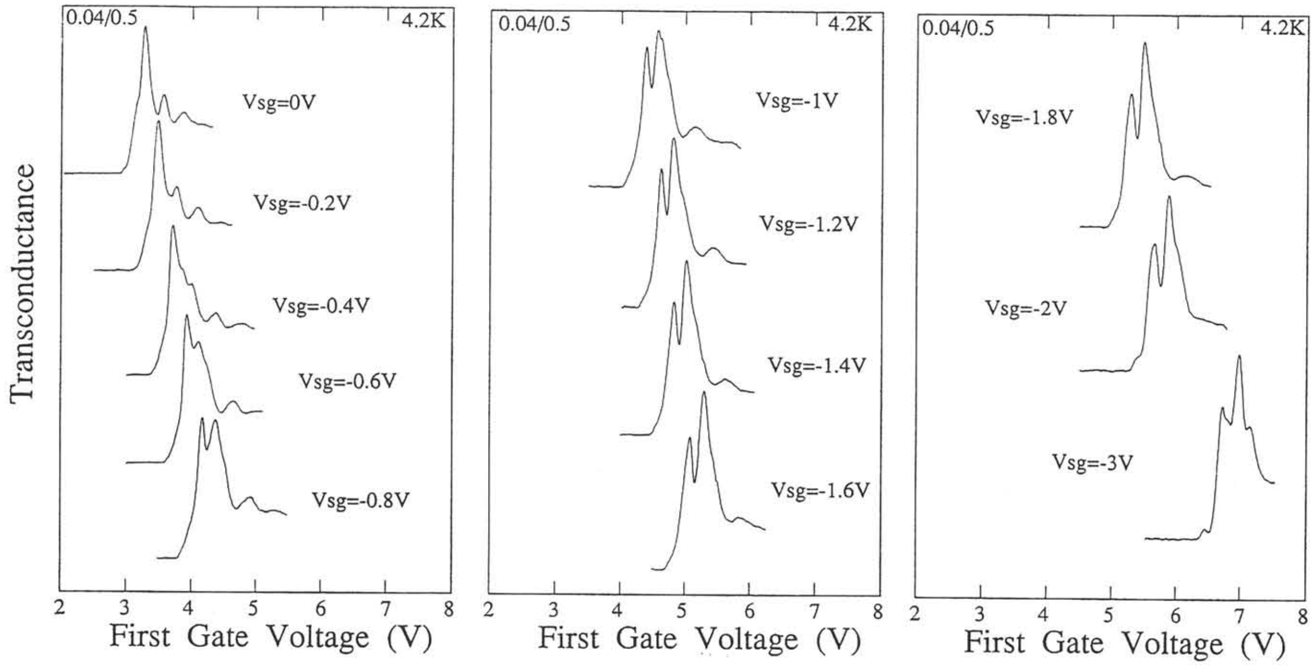

Fig. 4 Transconductance at 4.2K of the device shown in Fig.3. (first and second gate widths are 0.13μm and 0.55μm.)

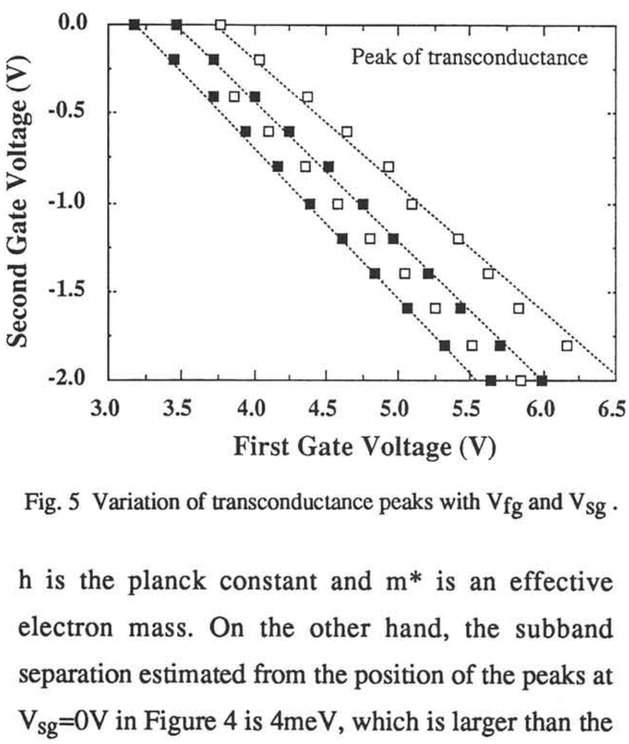

Fig. 5 Variation of transconductance peaks with V_{fg} and V_{sg}.

h is the planck constant and m* is an effective electron mass. On the other hand, the subband separation estimated from the position of the peaks at V_{sg}=0V in Figure 4 is 4meV, which is larger than the estimated value of 0.3meV. One of the reasons for this discrepancy is that the potential shape is not a complete square-well. The other is that the effective potential width at the Fermi energy is smaller than the fabricated gate width. When the first gare voltage is near the threshold voltage and the carrier density in the channel is low, there is a probability that the electrons gather at the center of the channel and the effective channel width becomes smaller than the fabricated one. A width of 40nm accounts for the discrepancy.

The most important point in Figure 4 and 5 is that the fine structure of transconductance changes continuously depending on the second gate voltage, that is, a new peak grows up between the first and second peaks and becomes the largest of all with decreasing second gate voltage. The density of states in a one-dimensional electron system is saw tooth shaped as shown in Figure 6. At V_{sg}=0V, the peaks observed in transconductance originate in quantized energy levels of the one-dimensional electron system in the channel. On the other hand, at V_{sg}=-1.2V, the quantized energy intervals under the second gate increases and hence one-dimensional subbands in the channel are as shown in Figure 6. Obviously the density of states at #1 (in Figure 6) increases with decreasing second gate voltage resulting in the

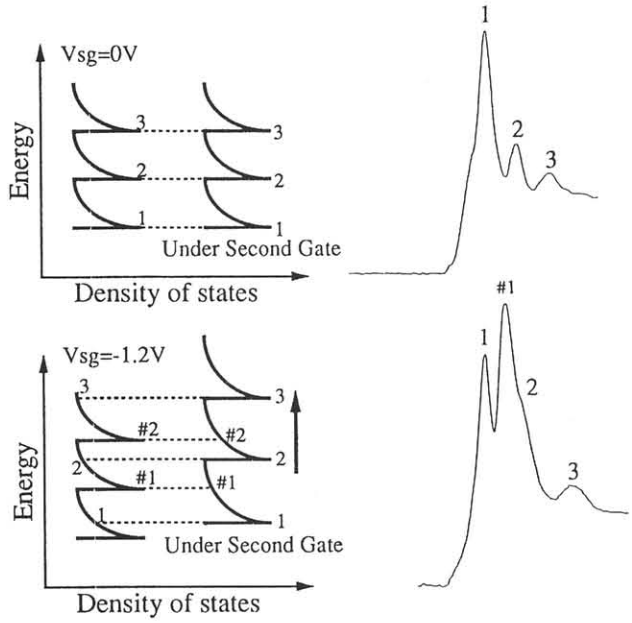

Fig. 6 Density of states at the channel with second gate voltage as a parameter.

generation of a new peak in transconductance. As can be seen in Figure 5, the intervals of the peaks become slightly larger with decreasing the second gate voltage, which is consistent with this model. Consequently, for good conductance, energy matching between subbands under the second gate and first gate may be necessary.

Conclusion

A new Si quantum device with a novel way of utilizing one-dimensional subbands has been proposed and fabricated by electron beam lithography. This device has dual layer gates in which one-dimensional quantized subbands are formed under the first (lower) gate and the intervals of the subbands are changed by the second (upper) gate resulting in drain current modulation. Transconductance modulation controlled by the second gate was observed at 4.2K.

Acknowledgements

The authors would like to thank K. Yagi, Y. Kawamoto, F. Murai and the people at the process integration center for device fabrication.

References

1) W. J. Skocpol, P. M. Mankiewich, R. E. Howard, L. D. Jackel, and D. M. Tennant, Phys. Rev. Lett. 56, 2865(1986)
2) A. B. Fowler, G. L. Timp, J. J. Wainer, and R. A. Webb, Phys. Rev. Lett. 57, 138(1986)
3) A. C. Warren, D. A. Antoniadis, and H. I. Smith, Phys. Rev. Lett. 56, 1858(1986)
4) T. Yoshimura, Y. Igura, T. Ichiguchi, H. Matsuoka, E. Takeda, and S. Okazaki, Jpn. J. Appl. Phys. 28, 2183(1989)