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Conduction Mechanism in Extremely Thin Poly-Si Wires -Width Dependence of Coulomb Blockade Effect-

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1. Introduction

Polycrystal silicon (poly-Si) are widely used and a key material in ultra large scale integrated circuits (ULSI). With reducing the size of electronic devices, the thickness and the width of the poly-Si wires becomes smaller, and may ultimately approach to a limit where a single electron effect determines the "on" and "off" states of the devices. Therefore, it is necessary to clear the influence of such small poly-Si wires more explicitly for utilizing them in the future ULSIs. The structural characteristics of the poly-Si wires strongly depend on the deposition method and condition, and directly influence the electrical properties. However, only a few studies have been reported to date [1-3].

In this study, we report a detailed electrical and structural characteristics of narrow poly-Si wires formed by low pressure chemical vapor deposition (LPCVD), which is most commonly used in the ULSI processes. We discuss the conduction mechanisms especially paying attention to the dependence on the wire width. We showed that the multiple Coulomb islands in series connection contribute to the low temperature electron conduction in the poly-Si wires. We also show, for the first time, the Coulomb gap increases with decreasing the wire width and we propose a new model for the conduction mechanism.

2. Experimental

A 150 nm oxide was grown on a p-type Si(100) (resistivity of 8~12 Ω·cm) by the wet oxidation at 1000°C. Amorphous Silicon (a-Si) film was deposited at 520°C on the oxide film by LPCVD using SiH_4, and it was polycrystallized by the annealing at 650 °C for 10 minutes in N_2. This two step process is effective to obtain a smooth surface. Doping was carried out by $POCl_3$ diffusion at 900°C for 150 s. Poly-Si wires were formed by electron-beam lithography and dry etching using the electron cyclotron resonance (ECR) etcher. Figure 1 shows the fabricated structure with a narrow poly-Si wire. The transistor operation is made using the substrate as a gate. The nominal wire length and the width of the fabricated pattern was 4-7 μm and 95-2000 nm, respectively. Finally, the passivation film (SiO_2) was deposited, and the Al electrode was formed.

3. Results and Discussion

3.1 Coulomb Diamond and Oscillation Characteristics

From the cross-sectional TEM micrograph (Fig.2), the film thickness of the poly-Si is from 4 to 9 nm and the grain size is from 15 to 50 nm. A zero-current Coulomb gap region and the modulation of the Coulomb gap by the gate voltage are clearly observed in the drain current (I_d) - drain voltage (V_d) characteristics (Fig.3). Since the size of the Coulomb diamond is not constant, the electron conduction is thought to be through multiple Coulomb islands which give rise to fluctuation in the Coulomb gap.

Figure 4 shows the temperature dependence of I_d - gate voltage (V_g) characteristics. The number of the observed peaks which are due to the Coulomb oscillation, gradually increases with temperature. Kemirink et al. interpreted the increase in the peak number with temperature for (Al,Ga)As heterostructure by a double-dot system [4]. Therefore, we estimated that our observations are also originated for the multiple Coulomb islands system.

3.2 Width Dependence of Coulomb Gap

Figure 5 shows the width dependence of I_d as a function of V_d at 5K. The Coulomb gap for the wire width of 145 nm is ~550 mV. It is too large for the Coulomb gap for a single island. From the temperature (80 K) where Coulomb oscillation disappears, Coulomb gap is estimated to be 14 mV. Therefore, the observed large Coulomb gap (~550 mV) suggests that the conduction is through multiple Coulomb islands connected in series. Assuming the same island size, the number of Coulomb island is estimated to be about 40 ($550 \div 14 \approx 40$). The Coulomb gap becomes small with increasing the wire width (Fig.5). For the width of 1000 nm, no Coulomb gap was observed. For the narrower width, Coulomb staircases in I_d-V_d characteristics were also noticeable in addition to the Coulomb gap in the higher voltage region.

The width dependence of the Coulomb gap is examined in detail and summarized in Fig.6. With increasing the wire width, the gap decreases and finally disappears at the width around 600 nm. It is considered that the number of the Coulomb islands, which contribute to the conduction mechanism, is reduced with increasing the wire width, because of the following model. A current path model in the poly-Si wire is illustrated in Fig.7. From the TEM observation, it was confirmed that the various size of grains exist in the poly-Si wire. Since the large grain has the small charging energy, the current tends to flow preferentially through the larger grains. When the wire becomes narrow, the probability for the electron to pass through the small grains becomes large. This leads to the observation of our large Coulomb gap for the narrow wires. When the wire become wide, the probability for the electron to meet the large grains becomes large, leading to the small Coulomb gap.

4. Conclusion

The conduction mechanism of narrow and extremely thin poly-Si wires have been investigated by the TEM and electrical measurements. The multiple dot conduction mechanism was newly proposed from the electrical measurements and their width dependence. The size of the Coulomb island estimated from the electrical properties coincides with the grain size of the poly-Si measured by the TEM.

The detailed width dependence of the Coulomb blockade effect in the poly-Si wire was, for the first time, investigated. From this study it is strongly suggested that the single electron effects becomes significant with scaling the device size in the future ULSIs

Acknowledgments

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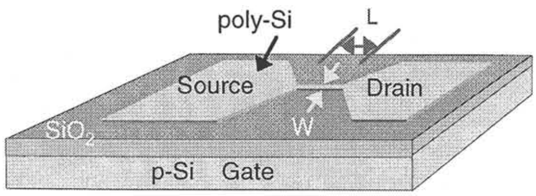

Fig. 1 Schematic diagram of fabricated structure of the transistor with a narrow wire of poly-Si.

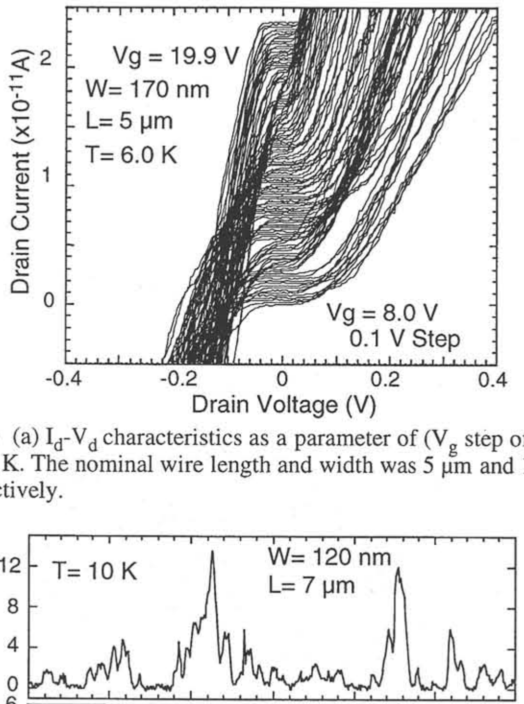

Fig. 3 (a) I_d-V_d characteristics as a parameter of (V_g step of 0.1 V) at 6.0 K. The nominal wire length and width was 5 μm and 170 nm, respectively.

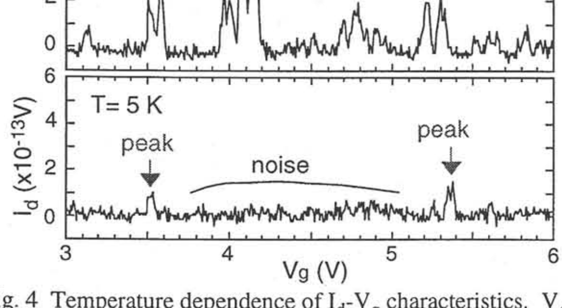

Fig. 4 Temperature dependence of I_d-V_g characteristics. V_d is constant at 10 mV. The nominal wire length and width were 4 μm and 120 nm, respectively.

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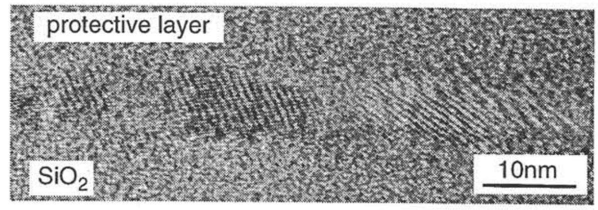

Fig. 2 Cross-sectional TEM micrograph of the fabricated poly-Si wire.

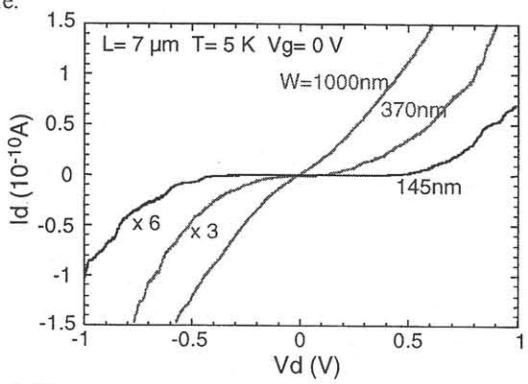

Fig. 5 Wire width dependence of I_d as a function of V_d at 5 K (V_g = 0 V).

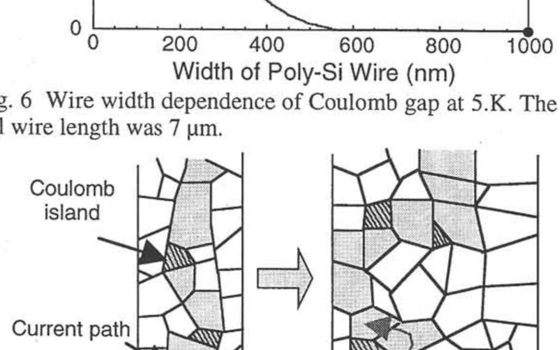

Fig. 6 Wire width dependence of Coulomb gap at 5.K. The nominal wire length was 7 μm.

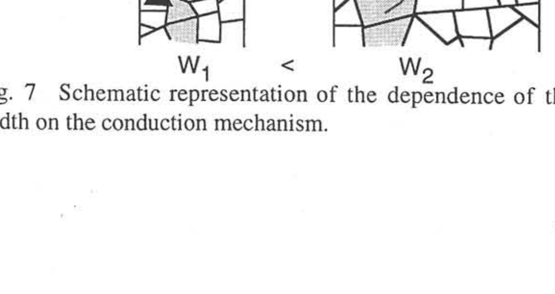

Fig. 7 Schematic representation of the dependence of the wire width on the conduction mechanism.