

Fabrication and Characterization of 14-nm-Gate-Length EJ-MOSFETs

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1. Introduction

We have fabricated Electrically variable shallow Junction MOSFETs (EJ-MOSFETs) with ultrashallow source/drain junctions to investigate transistor characteristics and physical phenomena in ultra-fine gate MOSFETs. By using electron-beam (EB) lithography and an ultrahigh-resolution EB resist (calixarene), we could achieve a gate length of 14 nm for the first time. Although significant short-channel effects (SCEs) were observed, the fabricated device exhibited transistor operation at room temperature.

2. Device Structure and Fabrication Process

Figure 1 shows a schematic cross-section of the EJ-MOSFET. The lower gate, which corresponds to the "gate" in conventional MOSFETs, controls the drain current. A positive upper-gate bias induces source/drain regions at the silicon surface. Since the source/drain regions are electrically induced, they are extremely shallow, typically 5 nm deep.

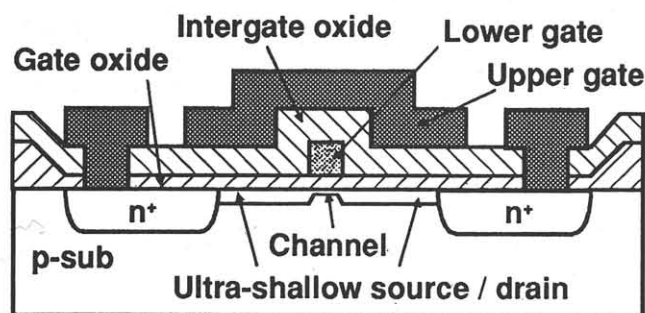


Figure 1: Schematic cross-section of an EJ-MOSFET

The EJ-MOSFET was fabricated in a similar way as conventional Si-MOSFETs. To suppress SCEs caused by the lateral expansion of the depletion layers, we used a relatively high boron concentration of $2 \times 10^{18} \text{cm}^{-3}$ within the substrate [1]. The boron concentration was controlled by means of the boron-ion implantation and the thermal drive-in. The n^+ -regions were formed by

arsenic-ion implantation. A gate oxide ($t_{ox} = 5 \text{ nm}$) was formed by thermal oxidation and a 40-nm-thick poly-Si layer was grown by chemical-vapor deposition (CVD). Phosphorus was doped into the poly-Si film in a POCl_3 atmosphere. The ultrahigh-resolution EB resist was spin-coated onto the poly-Si film and EB direct writing with a 5-nm beam diameter and a 50-kV acceleration energy was performed. After the developing procedure, the resist pattern was transferred to the poly-Si film by reactive-ion etching with CF_4 gas. By suppressing the electron-beam fluctuation and the residual resist after the development, we could achieve a shorter lower-gate length of 14 nm compared to the 32 nm which we previously reported [2]. Figure 2 shows an SEM top view of the poly-Si lower gate. Although there are fluctuations in the pattern edge, the lower gate was well defined. The 20-nm-thick intergate oxide layer was grown by CVD, which was followed by N_2 annealing and H_2 annealing. Finally, the upper gate and source/drain electrodes were formed by Au/Al evaporation.

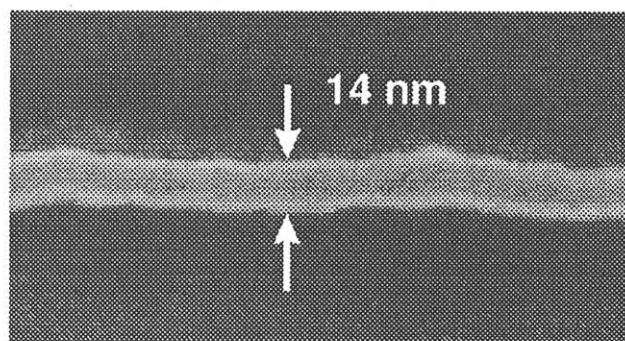


Figure 2: SEM top view of a 14-nm-gate-length poly-Si lower gate

3. Results and Discussions

We evaluated the electrical characteristics of fabricated devices with gate lengths (L_{LG}) that ranged from 14 nm to 98 nm at 300 K. To form source/drain regions, an upper-gate voltage (V_{UG}) of 7 V was applied.

Figure 3 shows the $I - V$ characteristics of a 14-nm-gate-length device. Although the device does not exhibit

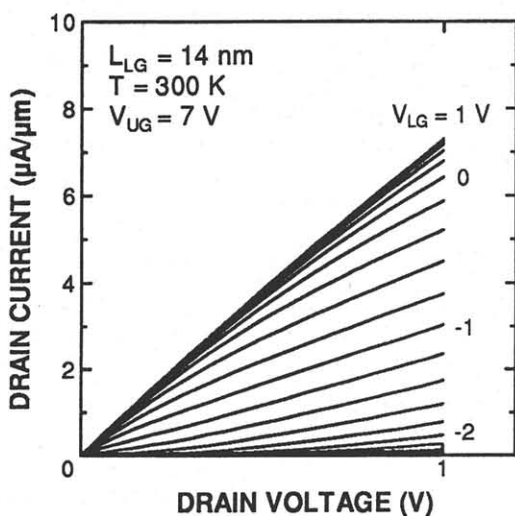


Figure 3: $I - V$ characteristics of a 14-nm-gate-length EJ-MOSFET at 300 K

clear saturation characteristics at a high drain bias, we can observe transistor operation in the 14-nm-gate-length regime. Figure 4 shows subthreshold characteristics for various devices. At $L_{LG} < 20$ nm, the curves shift toward the lower V_{LG} direction due to SCEs. Figure 5 shows the threshold voltage and the subthreshold slope (S-factor) as a function of L_{LG} . The SCEs cause significant V_{th} roll-off and degradation of the S-factor at $L_{LG} < 30$ nm. Taking the scaling principles into account, t_{ox} of 5 nm is too thick for the lower value of L_{LG} , which contributes to the SCEs. We will be able to reduce the SCEs by further reducing t_{ox} .

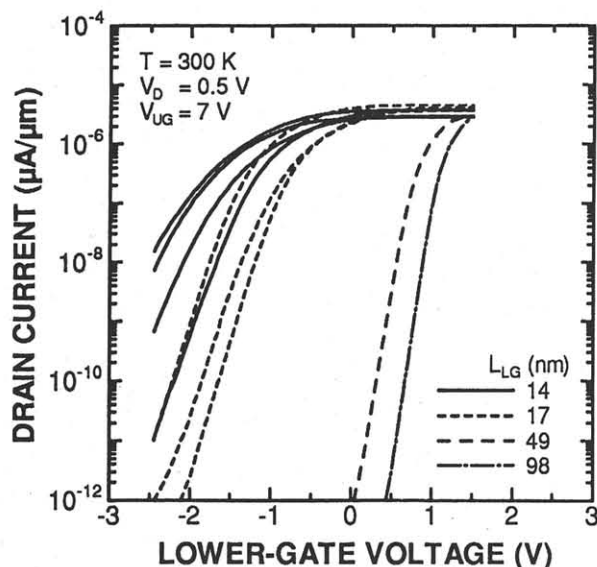


Figure 4: Subthreshold characteristics of various devices at 300 K

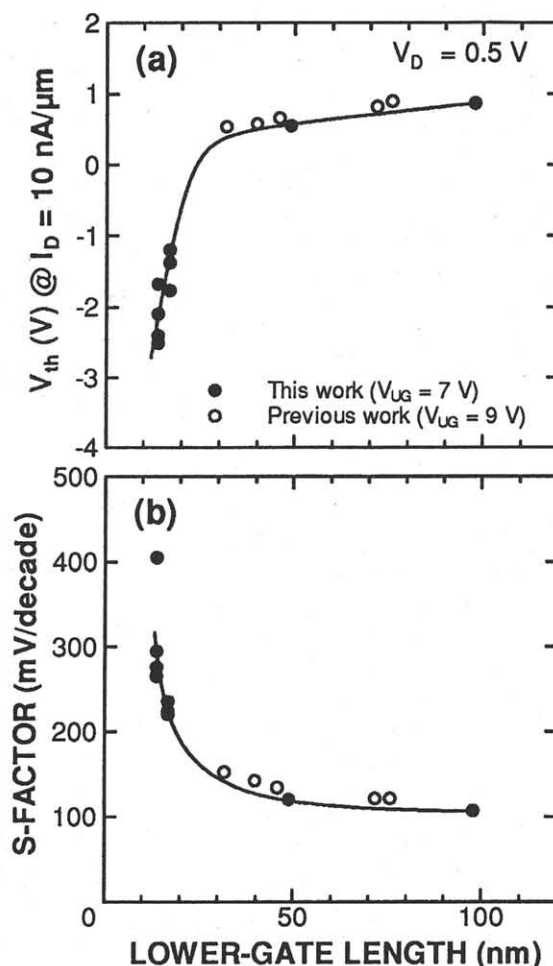


Figure 5: Threshold voltage (a) and S-factor (b) as a function of L_{LG} . Solid circles and open circles correspond to this work and our previous work [2], respectively. Since the previously reported device had a thicker intergate oxide of 24 nm, we applied V_{UG} of 9 V so that the equivalent electric field would be applied to the intergate oxide layer.

Acknowledgment

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