Gate oxide induced switch-on undershoot current observed in thin-film transistors

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The transient drain current of the single-grain silicon thin-film transistor with gate oxide deposited by electron cyclotron resonance plasma-enhanced chemical vapor deposition has been measured by applying a square signal on the gate and a constant low voltage between source and drain. Switch-on undershoot current has been observed, which can be attributed to the motion of space charge in gate oxide. Assuming there are some mobile ions in the gate oxide, we find the drift kinetics of the ions is quite similar to the mobile protons in SiO2, as reported in the literature. © 2005 American Institute of Physics. [DOI: 10.1063/1.1954896]

The technology of low-temperature polycrystalline silicon thin-film transistors (poly-Si TFT), fabricated by excimer laser recrystallization on a glass or plastic substrate, is being pursued to achieve the so-called system-on-panel. 1,2 A new development in TFT technology is the fabrication of location-controlled single-grain silicon TETFs (SG-TFTs) by the method referred to as micro-Czochralski or gain filter process. 3–5 Much higher electron mobilities than for standard laser-crystallized poly-Si TFTs are obtained with SG-TFTs (450 cm2/Vs). By exploiting the capability of this technology to take on many functions traditionally reserved for single-crystal devices, it is expected that a complete computer system will be fabricated on a glass or plastic substrate. In view of these applications, characterization of the transient behavior of SG-TFTs is of paramount importance for the optimum design of electronic circuits.

To improve the performance of the SG-TFTs, two different fabrication processes for the gate oxide have been used: low-pressure chemical vapor deposition (LPCVD) and electron cyclotron resonance plasma-enhanced chemical vapor deposition (ECR-PECVD). We found that the devices with ECR-PECVD oxide have a better Si/SiO2 interface and higher field-effect mobility. 5 The transient properties of these devices have been studied carefully. We have reported before that SG-TFTs with LPCVD oxide exhibit a switch-on overshoot (that is, the transient drain current after switch-on) higher than the static value. The effect has been attributed to trapping in the bulk or in the interface. 6–8 By contrast, in devices with ECR-PECVD oxide, a different transient effect has been observed. The transient drain current after switch-on is lower than the static value. We refer to this effect as “undershoot.” The purpose of this work is to understand the physical origin of the “undershoot.”

The n-channel SG-TFTs were fabricated inside location-controlled grains by the micro-Czochralski process. 3 After formation of the location-controlled grains, the Si film was patterned into islands by dry etching. A 137 nm thick SiO2 film was deposited by the ECR-PECVD at room temperature to serve as the gate dielectric. Microwaves with a frequency of 2.45 GHz, parallel to the magnetic field lines, were introduced to the chamber via a quartz window. SiH4 and O2 were used as source gases and the pressure was kept at 1 mTorr. The SiO2 was successively annealed at 333 °C in H2O/N2 ambient. The gate electrode was Al. The channel length and width were measured to be 3.21 and 2.88 μm, respectively. Control devices with ECR-PECVD gate oxide were fabricated on undoped (100)-oriented silicon-on-insulator (SOI), with the rest of the process being identical to that of the SG-TFTs.

The transient measurement setup has been reported before. 6,7 As shown in Fig. 1, a train of pulses was applied to the gate by an Agilent 33250A wave form generator. The source was grounded and a constant voltage (VDS=0.1 V) was applied to the drain by a Keithley 230 voltage source. The transient current was amplified by a Keithley 428 current voltage converter and detected by a LC584AL digital oscilloscope. The output signal was averaged over 1000 periods to reduce the noise. The pulse rise time was set to 20 ns, chosen to be comparable with those typically used in TFT digital circuitry. All of the measurements were controlled through LABVIEW. The transient measurements were

\[ V_{GS,max} - V_{GS} - V_{off} \]

\[ V_{DS} = 0 \]

\[ V_{DS} = 0.1 \text{ V} \]

\[ V_{off} \]

\[ t_{off} \]

FIG. 1. Wave form used in the transient measurements.

\[ V_{GS} \]

\[ V_{DS} \]

\[ t_{on} \]

\[ t_{off} \]
undershoot values for the two relaxation times \( t_1 \) and \( t_2 \) shows that the relaxation time \( t_2 \) decreases with the increase of temperature.

As shown in Fig. 2(a), the drain current after switch-on increases with time until it reaches the static value (undershoot). The transient current can be fitted to the following expression:

\[
I_{DS}(t) = I_{\text{static}} - \Delta I_1 \exp(-t/\tau_1) - \Delta I_2 \exp(-t/\tau_2),
\]

where \( I_{\text{static}} \) is the static value, and \( \Delta I_1 \) and \( \Delta I_2 \) are the undershoot values for the two relaxation times \( \tau_1 \) and \( \tau_2 \), respectively. \( \tau_1 \) corresponds to the faster relaxation process, which is tens of milliseconds long, and \( \tau_2 \) corresponds to a slower process lasting hundreds of milliseconds. Figure 3 shows that the relaxation time \( \tau_2 \) decreases with the increase of \( V_{GS,max} \).

As shown in Fig. 2(b), the undershoot current of SOI TFTs exhibits a similar relaxation time constant \( \tau_2 \) of about hundreds of milliseconds. Figure 3 shows the relaxation time \( \tau_2 \) as a function of \( V_{GS,max} \). This is a strong indication that the undershoot is due to the ECR-PECVD gate oxide.

The undershoot implies that the number of electrons in the channel increases with time after switch-on. If we assume that there are mobile space charges in the gate oxide, the effect on the channel electron density is described by

\[
V_{GS} = \frac{1}{\varepsilon_e\varepsilon_0} \left[ |Q_c| d - |Q_+| c_+ + |Q_-| c_- \right] + \Psi_s,
\]

where \( \varepsilon_e \) is the relative dielectric constant of the gate oxide, \( Q_c \) is the channel charge density per unit area, \( Q_+ \) and \( Q_- \) are the positive and negative charge density per unit area in the oxide film, respectively, \( c_+ \) and \( c_- \) are the distances of the centroids of positive and negative charge from the metal/gate/insulator interface, respectively, \( d \) is the thickness of the gate oxide, and \( \Psi_s \) is the surface potential. Equation (2) indicates that the change of space charge density or the motion of space charge in the oxide can influence the electron density in the channel. The first case corresponds to space charge injection from the gate metal or the channel, the second case can be regarded as dielectric relaxation of the oxide film. In the case of space charge injection, two types of processes may occur with positive \( V_{GS} \): electron injection from the channel, which would result in a lower channel electron density, and hole injection from the gate metal that would give rise to higher channel electron density and consequently higher drain current. Hence, the undershoot could be due to hole injection from the gate. However, hole injection from the metal gate due to Schottky emission or Poole-Frenkel emission is expected to yield a nonlinear relationship between the injection current and the applied electric field. By contrast, as shown in Figs. 2(a) and 2(b), the undershoot value depends linearly on the applied gate voltage. We consider next the motion of space charge in the oxide. When a positive gate voltage is applied, positive charges move away from the gate and/or negative charges move toward gate; therefore \( c_+ \) increases and/or \( c_- \) decreases. According to Eq. (2), this results in an increase of electron density in the channel, and the undershoot.

To further understand the undershoot current, we do the variable temperature measurements on the SG-TFT in the temperature range between 220 and 350 K. We find the relaxation time \( \tau_2 \) decreases with the increase of temperature and shows a thermal activation behavior: \( \tau_2 \propto \exp(\Delta E/kT) \) with an activation energy of \( \Delta E \approx 0.08 \) meV. However, the undershoot current corresponds to a very complicated process. Assuming it is induced by the diffusion of space charge in the gate oxide, \( \tau_2 \) would be influenced by both the diffu-

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**Fig. 2.** (a) Undershoot current observed in a 3.2 \( \mu \)m \( \times \)2.9 \( \mu \)m \( n \)-channel SG-TFT. \( V_{GS}=0.1 \) V. From top to bottom, \( V_{GS,max} \) varies from 8.5 to 1.5 V. \( V_{GS}=0 \) V. Inset: The undershoot value \( \Delta I = [I_{DS}(t=20 \text{ ns})-I_{DS}(t=0.5 \text{ s})] \) for different \( V_{GS,max} \). (b) Undershoot current observed in a 1.8 \( \mu \)m \( \times \)2.0 \( \mu \)m \( n \)-channel SOI-TFT. \( V_{GS}=0.1 \) V, \( V_{GS}=3 \) V. Inset: The undershoot value \( \Delta I \) for different \( V_{GS,max} \).

**Fig. 3.** The relaxation time \( \tau_2 \) as a function of \( V_{GS,max} \). Symbols: round (SG-TFT), square (SOI-TFT).

**Fig. 4.** Logarithmic plot of \( dQ/dt \) vs temperature of a 3.2 \( \mu \)m \( \times \)2.9 \( \mu \)m \( n \)-channel SG-TFT. \( V_{GS}=0.1 \) V and \( V_{GS}=8.0 \) V. The best fitting dashed line is shown. The activation energy \( \Delta E \approx 0.32 \) eV.
Assuming there are only positive mobile charges in the gate oxide.

Another alternative approach is to calculate the drain current change at the beginning of switch-on: \( dI_d/dt \big|_{t=0} \). Assuming there are only positive mobile charges in the gate oxide, we have

\[
\begin{align*}
dI_d/dt \big|_{t=0} &= - (W/L)C_{ox} \mu_n V_{th} dV/dt, \\
dV/dt &= \frac{1}{\varepsilon_0 \varepsilon_r} Q_r \nu(T) = \frac{1}{\varepsilon_0 \varepsilon_r} Q_r R_{fi}/\tau_h,
\end{align*}
\]

where \( V_{th} \) is the threshold voltage of the device, \( \mu_n \) is the field-effect mobility of electrons in the channel, \( R_{fi} \) is the hopping distance, and \( 1/\tau_h \) is the hopping rate of positive charge. Thus, \( dI_d/dt \big|_{t=0} \) is proportional to the hopping rate. As shown in Fig. 4, \( dI_d/dt \big|_{t=0} \) exhibits a thermal activation process with the activation energy of \( \Delta E_2 \approx 0.32 \text{ eV} \).

To confirm the mechanism of undershoot current discussed earlier, we have fabricated metal oxide semiconductor (MOS) devices with ECR-PECVD oxide and LPCVD oxide on \( p \)-type Si wafer with \( N_A = 10^{16} \text{ cm}^{-3} \). The oxide layers were fabricated with the same process as SG-TFTs. The thicknesses of ECR-PECVD and LPCVD oxide films are 126.2 and 131.5 nm, respectively. The \( C-V \) curves of these devices have been measured at different frequencies. The devices with ECR-PECVD oxide show unstable flatband voltage, whereas the LPCVD oxide ones show a very stable flatband. Thus, we conclude that the space charge motion in the ECR-PECVD oxide film is responsible for the variation of the flatband voltage.

Figure 5 shows the calculated dielectric constants of the two films as a function of frequency extracted from the capacitance measured at \( V_{gs} = -10 \text{ V} \) (accumulation condition). The ECR-PECVD oxide has a much higher dielectric constant and a large frequency dispersion, which is due to the space charge relaxation in the oxide.\(^{10,11}\) Therefore, the MOS \( C-V \) measurements versus frequency are consistent with the transient measurements in the SG-TFTs.

It is difficult to decide the nature of the space charge in our ECR-PECVD oxide films from the measurements described earlier. Since the undershoot value is proportional to the applied voltage, the effect can be due to the relaxation of dipoles formed by impurity ions in the oxide film\(^{11} \) or the drift of ions/localized charges. A similar drain current relaxation lasting hundreds of milliseconds has been observed in SOI MOS field-effect transistor by Vanheusden et al.\(^{12} \) This relaxation has been attributed to the drift of protons in the gate dielectric. The activation energy for \( dI_d/dt \big|_{t=0} \) we obtain in our measurement (\( \sim 0.32 \text{ eV} \)) is much lower than the value Vanheusden et al.\(^{12} \) reported (\( \sim 0.82 \text{ eV} \)), while it is quite similar to the value Devine et al.\(^{13} \) obtained (\( \sim 0.38 \text{ eV} \)). We expect that protons can be easily introduced in our SiO\(_2\) films during deposition or annealing. Thus, the undershoot current we observed in SG-TFTs could be due to the drift of protons in the gate oxide.

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