Electron mobility in amorphous silicon thin-film transistors under compressive strain

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We evaluated amorphous silicon thin-film transistors under uniaxial compressive strain of up to 1%. The on-current and hence the electron linear mobility decrease. The off-current, leakage current, and the threshold voltage do not change. The mobility decreases linearly with applied compressive strain. Upon the application of stress for up to 40 h the mobility drops “instantly” and then remains unchanged. We conclude that compressive strain broadens both the valence and conduction band tails of the a-Si:H channel material, and thus reduces the effective electron mobility. © 2001 American Institute of Physics. [DOI: 10.1063/1.1418254]

Flexible, lightweight, active-matrix back planes are needed for new display applications, such as electronic paper, large-area curved electronic screens, and flexible smart labels, and for sensor skins and electrotextiles. The active matrix plane, whether used to control liquid crystals, bistable electrophoretic materials, or organic light-emitting diodes, most often is made of amorphous silicon thin-film transistor (a-Si:H TFT) pixel switches. Depending on the application these transistors will be subjected to tensile or compressive strain. Therefore, the electrical performance of a-Si:H TFTs under strain needs to be carefully studied and understood.

We have shown that the strain in a-Si:H TFTs from bending can be substantially reduced if very thin and/or compliant substrates are used. 1–3 We also have observed that TFTs respond differently to tensile and compressive strain. They are found to function properly after the application of tensile strain of up to ~0.5% (where they fail mechanically) and after compressive straining of up to ~2% (with no failure observed so far). 4 In this letter we report changes in the electron field effect mobility in a-Si:H TFTs during application of compressive strain of up to 1%.

We fabricated arrays of a-Si:H TFTs on 51-μm-thick polyimide at the maximum process temperature of 150 °C. First, the polyimide substrate was coated on both sides with a 0.5-μm-thick layer of SiN x. All TFTs had the following structure: ~100-nm-thick Ti/Cr layer as gate electrode, ~360 nm of gate SiN x, ~100 nm of undoped a-Si:H, 180 nm of passivating SiN x, ~50 nm of (n +) a-Si:H, and ~100-nm-thick Al for the source-drain contacts. Fabrication details are given elsewhere. 5 The cross-sectional view of this structure is shown in the inset to Fig. 1. After fabrication, the SiN x layer on the back of the substrate was etched away and the transistors were annealed in forming gas. Figure 1 shows typical transfer characteristics for these devices. The off-current is ~3×10−12 A, the on/off current ratio >106, the threshold voltage ~3 V, and the subthreshold slope ~0.5 V/decade. The electron linear mobility, calculated from the transfer characteristic for drain-to-source voltage V ds = 0.1 V, is ~0.45 cm2/V s.

We separately deposited a ~0.7-μm-thick layer of a-Si:H on Corning 7059 glass and measured the transmission spectrum, the photothermal deflection spectroscopy and the constant photocurrent method, 6 to evaluate the slope of the valence band edge (the Urbach energy), 7 and the number of dangling bonds. 8 This material, which is identical to the channel material used in our TFTs, has an Urbach energy of ~52 meV and a dangling bond density of ~2×1015 cm−3.

We compressively strained individual transistors by inward cylindrical bending. In most cases the bending direction was parallel to the source-drain current path, as shown by arrows in Fig. 1. In this case the TFT channel length was squeezed. A few TFTs were also tested with the bending direction perpendicular to the source-drain current path. In this case the TFT channel width was squeezed. Single TFTs were bent to different radii of curvature R, ranging from 70 to 1.6 mm. Transfer characteristics like those of Fig. 1 were measured at each bending radius. Some TFTs were measured at several R, while others were bent permanently to a fixed R, to monitor the change in the transfer characteristics for ~40 h. From each set of transfer characteristics we extracted the off-current I off, on-current I on, gate leakage current I leak, linear mobility μ, threshold voltage V th, and subthreshold slope S. The definition of these currents is as follows: the off-current is the smallest drain-to-source current at V ds = 10 V,

![FIG. 1. Transfer characteristics of a-Si:H TFT fabricated on ~51-μm-thick polyimide foil. The source was grounded. The inset shows the TFT cross section.](image_url)
the on-current is the drain-to-source current for $V_{ds} = 10 \, \text{V}$ and $V_{gs} = V_{th} + 10 \, \text{V}$, and the leakage current is the gate-to-source current for $V_{ds} = 10 \, \text{V}$ and $V_{gs} = 20 \, \text{V}$. $V_{th}$ and $\mu$ were calculated from the transfer characteristic for $V_{ds} = 0.1 \, \text{V}$ using the MOSFET equations for the linear regime, while $S$ was obtained by fitting an exponential function to the subthreshold region of the transfer characteristic for $V_{ds} = 10 \, \text{V}$. To obtain reference values for these parameters, each TFT was measured first before any compressive strain was applied. We calculated the compressive strain at the $\text{SiN}_x/\alpha$-Si:H interface of the TFTs using Eq. (1) of Ref. 4. Young’s modulus of our polyimide substrate is 5 GPa and we assumed 183 GPa for all TFT layers. The highest strain, at the smallest bending radius $R = 1.6 \, \text{mm}$, was $\sim 1\%$.

Upon application of compressive strain we observed a slight decrease in the on-current $I_{on}$ and hence the linear mobility $\mu$. The changes in the off-current $I_{off}$ and leakage current $I_{leak}$ remained within experimental error and we concluded that they did not change. There was a large scatter in the threshold voltage $V_{th}$ and the subthreshold slope $S$. Nevertheless, $S$ is rising slightly with increasing compressive strain. The scatter in $S$ and $V_{th}$ did not allow investigating whether they are correlated, as they should be in theory.

The mobility decreased linearly with increasing compressive strain, as shown in Fig. 2. Figure 2(a) depicts the relative mobility $\mu/\mu_0$ as a function of compressive strain $\eta$, where $\mu$ is the linear mobility under an imposed compressive strain and $\mu_0$ is the initial linear mobility. Each symbol on the graph represents a different TFT. The empty and full symbols correspond to TFTs with the parallel and perpendicular bending direction, respectively. There is no qualitative difference in the behavior of $\mu/\mu_0$ as a function of strain, but quantitatively the values of $\mu/\mu_0$ remain slightly larger in the perpendicular bending direction. A linear fit to all experimentally measured mobilities gives: $\mu/\mu_0 = 1 - \eta/4$, when the strain is expressed in percent.

Figure 2(b) shows the relative subthreshold slope $S/S_0$, where $S$ is the subthreshold slope at a given compressive strain and $S_0$ is the initial slope. While the spread in the experimental data is quite large, the subthreshold slope is seen to rise slightly with increasing compressive strain.

Upon imposition of a given compressive strain, the drop in the mobility was “instantaneous” (on the time scale of 5 min) and it did not change while the strain was maintained for $\sim 40 \, \text{h}$. The off-current $I_{off}$ and the leakage current $I_{leak}$ did not change.

The drop in mobility most likely is a consequence of the broadening of the conduction band tail of the $\alpha$-Si:H channel material under compression. In crystalline silicon the electron and hole mobilities depend on valley degeneracy and on scattering by thermal vibrations of the lattice and by ionized impurities. The $\alpha$-Si:H has no crystal symmetry, we did our measurements at constant temperature, and the $\alpha$-Si:H is of device quality and does not contain phosphorus or boron impurities, which rules out these mechanisms of increased free electron scattering, if they were important at all in $\alpha$-Si:H. During our bending experiments the amorphous silicon network is squeezed by no more than $1\%$, which causes an insignificant change in the scattering length. Bond length reduction therefore does not reduce the mobility of free electrons, which is effectively set by scattering on every silicon atom. However, in $\alpha$-Si:H TFT channels the free electron mobility is reduced to an effective mobility by frequent trapping in the conduction band tail states of the $\alpha$-Si:H channel material. Thus the electron field effect mobility measured in $\alpha$-Si:H TFTs depends sensitively on the width of the conduction band tail. For these reasons we consider a change in the slope (width) of the conduction band tail upon compression to be the most likely cause of mobility reduction.

The study of published research reveals a link between the conduction band tail width and hydrostatic compression. First, the electron linear mobility in $\alpha$-Si:H TFTs is correlated with the Urbach energy of the $\alpha$-Si:H channel material, because the slopes of the conduction and valence band tails are correlated: a large Urbach energy $E_U$ means a wide conduction band tail and a low electron mobility. The data of Refs. 11 and 12 suggest that the $\sim 25\%$ reduction in the electron mobility, which we observed at the compressive strain of $\sim 1\%$, is correlated with a 1.5 meV increase in the Urbach energy of the $\alpha$-Si:H channel material. Next, Cody et al. found that in $\alpha$-Si:H the Urbach energy $E_U$ and the optical gap $E_g$, which are controlled by the degree of disorder, structural and thermal, are correlated as $\Delta E_U \sim -6.2 \times \Delta E_0$. Assuming that strain-induced disorder follows the same dependence, an increase in $E_0$ of $\sim 1.5 \, \text{meV}$ should cause $\sim 10 \, \text{meV}$ reduction in $E_g$. Last, Welber and Brodsky showed experimentally that $E_g$ decreases with increasing hydrostatic pressure $P$ (compressive stress) as $(dE_g/dP)_T \sim -0.7 \times 10^{-11} \text{eV/Pa}$. Thus a 10 meV reduction in $E_g$ requires a hydrostatic pressure of $\sim 1.4 \, \text{GPa}$. Taking 60 GPa for the bulk elastic modulus of $\alpha$-Si:H by hydrostatic compression, $1.4 \, \text{GPa}$ will cause $\sim 2\%$ compression. By thus linking our observed reduction in electron mobility to the likely effect of a hydrostatic compression of $\sim 2\%$, we can plausibly explain the mobility reduction as a consequence of increased disorder.

Finally, we need to add a few qualifying comments. In our discussion we neglected piezoresistive changes in the contact resistance of the $\alpha$-Si:H TFTs. This effect has been observed in microcrystalline silicon, but has not yet been studied in $\alpha$-Si:H. The decrease in the electron mobility in $\alpha$-Si:H TFTs and the reduction in band gap of $\alpha$-Si:H under compressive stress imply that a piezoresistive effect does exist. The effect of reducing the TFT channel length by strain...
on the calculated values of mobility will be negligible.

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7 F. Urbach, Phys. Rev. 92, 1324 (1953).