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Mechanical strain-induced defect states in amorphous silicon channel layers of thin-film transistors

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A B S T R A C T

In this study, we examined mechanical strain-induced defect states in hydrogenated amorphous silicon (a-Si:H) channel layers of thin-film transistors (TFTs) bent with a curvature radius of 18 mm. When strain is applied to the TFTs, our devices feature strain-induced variations in threshold voltage (~1.47 V), subthreshold swing (~0.36 V/dec), and field-effect mobility (~0.031 $cm^2 V^{-1} s^{-1}$). The electrical characteristics of a-Si:H TFTs on bendable substrates under mechanical strain are explained by the variation in the density of states (DOS) of defects in the channel layers. Our simulation work on the DOS in the a-Si:H channel layers under mechanical strain reveals that the mechanical strain causes not only the deformation of the density of mid-gap defect states but also an increase in the band-tail states within the band gap.

1. Introduction

Amorphous semiconductor thin-film transistors (TFTs) have been one of the main components of bendable displays [1–11] because amorphous semiconductors are preferred over polycrystalline ones, owing to the better uniformities of their device characteristics and lower processing temperatures [1–3]. In particular, hydrogenated amorphous silicon (a-Si:H) TFTs have been considered by the industry as a promising component for bendable displays, including electronic paper, because the fabrication process and the uniformity for their large-size and low-cost panels are well established [4,5]. For the application of a-Si:H TFTs to bendable displays, the mechanical stability of a-Si:H TFT channel layers is an important consideration because it limits the degree of flexibility. A deep investigation of the density of states (DOS) of defects in a-Si:H channel layers induced by mechanical strain is a basis for the improvement of amorphous semiconductor TFTs.

In amorphous silicon, significant DOS of defects exist within the band gap. The DOS plays a crucial role in determining the electrical characteristics of amorphous semiconductor TFTs. Moreover, the deformation of the defect states induced by mechanical strain substantially affects their electrical characteristics [6–8]. So far, limited studies on the variation of the DOS under mechanical stress have been reported with regard to a-Si:H TFTs.

In this study, the electrical characteristics of a-Si:H TFTs on plastic substrates were investigated while applying mechanical strain, and the variation of the DOS of defects in the a-Si:H channel layers was studied intensively.

2. Device structure, experiment, and simulation

Fig. 1 shows the schematic design of a bottom-gate a-Si:H TFT under mechanical strain. The channel width and length are both 10 μm. The dimensional parameters are the channel width (10 μm), channel length (10 μm), channel thickness (150 nm), Mo gate electrode thickness (120 nm), gate insulator thickness (400 nm), SiN_x passivation layer thickness (400 nm), and buffer layer thickness (150 nm).

The a-Si:H TFTs on polyimide (PI) substrates with a 25-μm thickness were placed on bending stages for applying tensile/compressive strains to these TFTs, as shown in Fig. 2. These TFTs were bent with a curvature radius of 18 mm in a direction parallel to the source and drain electrodes. To observe the reversible changes in the characteristics of TFTs without any mechanical destruction, we chose a curvature radius of 18 mm.

To analyze the DOS of defects in the a-Si:H channel layer induced by mechanical stress, our 3-D numerical simulations were performed using commercial device simulator Silvaco ATLAS (version 5.20.2 R, Silvaco International). In our simulation, the bulk states density and the interface states density are used to define the density of defect states in

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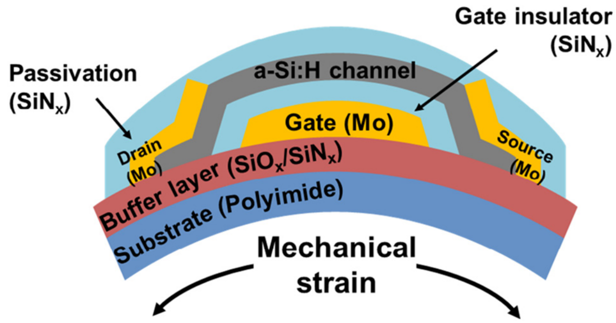

Fig. 1. Schematic of the a-Si:H TFT under mechanical strain.

amorphous silicon. The mobility gap (E_{mg}) of a-Si:H is 1.75 eV in our simulation.

3. Results and discussion

The bent TFTs with a curvature radius of 18 mm experience 0.07% strain; this strain value is estimated by [12]

$$\text{strain}(\%) = \frac{(\text{thickness of PI substrate} + \text{thickness of total film})}{2 \times R_C} \times 100 \quad (1)$$

where R_C is the curvature radius. The experimental data points of drain-to-source current (I_{DS}) *versus* gate-to-source voltage (V_{GS}) obtained from the flat and mechanically strained TFTs are fitted in Fig. 3 by the simulation curves. The threshold voltage (V_{TH}), subthreshold swing (*SS*), and field-effect mobility (μ_{FE}) vary with the tensile/compressive mechanical strain. In the comparison between the I_{DS}-V_{GS} curves of the flat and tensile strained TFTs in Fig. 3(a), with the tensile strain, the V_{TH} shifts from 0.77 to 1.49 V, the *SS* decreases from 1.24 to 1.18 V/dec, and the μ_{FE} increases from 0.207 to 0.238 $cm^2\ V^{-1}\ s^{-1}$. With the tensile strain, the off-current decreases from 6.0×10^{-12} to 3.2×10^{-12} A at $V_{GS} = -15$ V, whereas the on-currents are almost constant. The comparison between the I_{DS}-V_{GS} curves of the flat and compressive strained TFTs in Fig. 3(b) reveals that, with the compressive strain, the V_{TH} shifts from 0.77 to 2.24 V, the *SS* increases from 1.24 to 1.60 V/dec, and the μ_{FE} decreases from 0.207 to 0.189 $cm^2\ V^{-1}\ s^{-1}$. With the compressive strain, the on-current decreases from 4.4×10^{-8} to 3.5×10^{-8} A at $V_{GS} = 15$ V, whereas the off-currents are almost constant. It is noted that the variations in electrical characteristics are temporary within the safe region. When the mechanical strain is removed, the electrical characteristics are recovered in the flat condition [6].

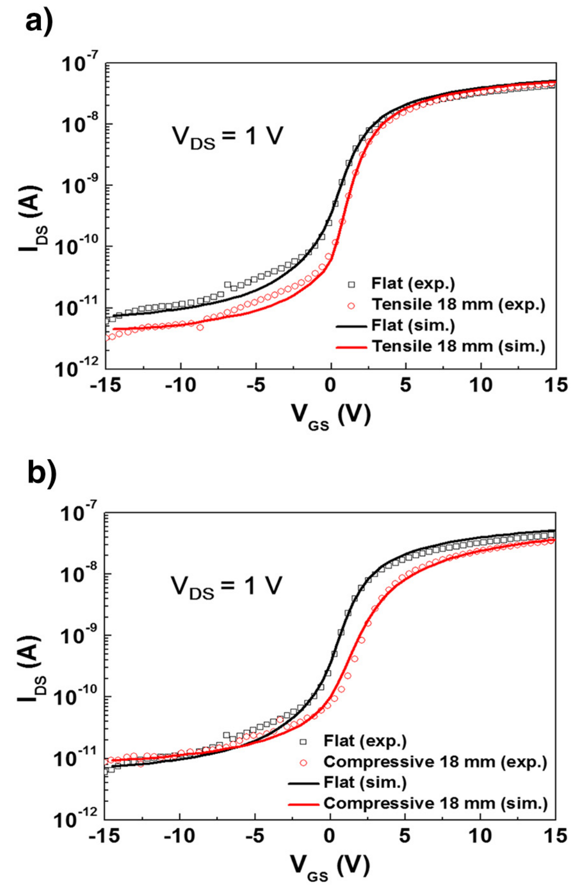

Fig. 3. Experimental *I*-*V* transfer curves with the simulation data in the flat condition: (a) under tensile strain and (b) under the compressive strain (with a curvature radius of 18 mm).

A possible reason for the variation in the electrical characteristics is the change in DOS of defects in the band gap. Many defect states are present within the band gap of the amorphous semiconductor. The disorder in the atomic structure causes a broadening of the valence and conduction bands leading to band tails, and the presence of dangling bonds in the Si channel interface results in the formation of defect states near the middle of the band gap. These defect states are called the band-tail states and mid-gap defect states, respectively. The mechanical strain causes the deformation of the defect states. In particular, the interface between the Si channel and the insulator layer is more vulnerable than the inner Si channel. In the interface, the mechanical strain generates more dangling bonds, resulting in the rearrangement of mid-gap

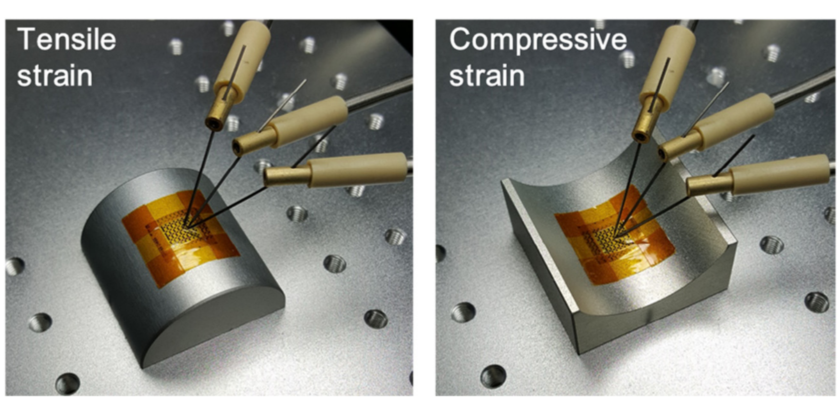

Fig. 2. Image of the bending stages.

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