Bendable integrated circuits on plastic substrates by use of printed ribbons of single-crystalline silicon

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This letter presents studies of several simple integrated circuits—n-channel metal-oxide semiconductor inverters, five-stage ring oscillators, and differential amplifiers—formed on thin, bendable plastic substrates with printed ribbons of ultrathin single-crystalline silicon as the semiconductor. The inverters exhibit gains as high as 2.5, the ring oscillators operate with oscillation frequencies between 8 and 9 MHz at low supply voltages (~4 V), and the differential amplifiers show good performance and voltage gains of 1.3 for 500 mV input signals. The responses of these systems to bending-induced strains show that relatively moderate changes of individual transistors can be significant for the operation of circuits that incorporate many transistors. © 2007 American Institute of Physics. [DOI: 10.1063/1.2742294]

Large area, mechanically flexible electronics could enable innovative classes of devices for information display, medical diagnostics, X-ray imagers, and other systems. Such applications require high performance and robust technologies for the circuits. A variety of semiconductor materials have been explored, ranging from amorphous silicon, to small molecule organics and polymers, to polycrystalline silicon, and other inorganics, to carbon nanotubes.1–5 An alternative approach uses ribbons, wires, platelets, and other structural forms of single-crystalline inorganic semiconductors.6,7 We and others have recently demonstrated this strategy by building a variety of devices including high performance n-channel metal-oxide semiconductor field-effect transistors (NMOSFETs) that use single-crystalline silicon ribbons and membranes with submicron thicknesses, which we refer to as microstructured silicon.8,9 This letter presents circuits that incorporate multiple transistors of this type, including n-channel metal-oxide semiconductor (NMOS) inverters (logic gates), five-stage ring oscillators, and differential amplifiers, all supported on thin, flexible plastic sheets. Studies of the changes in electrical properties caused by mechanical bending reveal variations that, although small on an individual device basis, can be significant for operation of the circuits. These results could represent important considerations for the design of flexible electronic systems.

The fabrication of the devices presented here began with the formation of contact doped regions in the top layer of a silicon-on-insulator wafer (Soitec unibond with a 290 nm thick top Si layer and a 400 nm thick buried oxide layer).8 For cost sensitive applications, related approaches that exploit commodity bulk wafers can be used.10 Photolithography and etching processes defined ribbons from the top silicon layer; printing techniques delivered these ribbons in organized arrays to device substrates consisting of polyimide (PI) sheets (25 μm) coated with thin adhesive layers (~1.0 μm) of liquid PI precursor (polyamic acid, Sigma-Aldrich Inc.). Layers of SiO2 (100 nm) formed by plasma-enhanced chemical vapor deposition served as the gate dielectrics. Etching through these layers and then defining metal patterns (Cr/Au, 5 nm/100 nm) by photolithography and lift-off created the source, drain, and gate electrodes for the transistors as well as the device interconnects needed to form circuits. Details of these processing procedures have been described elsewhere.7,8

Figure 1(a) shows representative current-voltage characteristics of an NMOSFET that has a channel length (Lc) of 2 μm, contact overlap (Lo) of 1.5 μm, and channel width (W) of 200 μm. The effective device mobilities, calculated using standard MOS model,7 are ~550 and ~450 cm2/V s in the linear and saturation regimes, respectively. The on/off ratio is ~105, with a threshold voltage of ~0.1 V. The maximum gate-swing hysteresis, for the voltage ranges used here, is ~0.5 V, which we believe is likely caused by some amount of charge trapped in the SiO2 and/or by defects associated with oxygen deficiencies at the interface between the Si and SiO2 layer.11 This moderate level of hysteresis does not represent a fundamental limit; it can be reduced further by appropriate choice of adhesive layer for the transfer and design of silicon ribbon structures. Devices of this type can operate at high frequencies. Figure 1(b) shows the cutoff frequency fT as a function of drain current, determined without de-embedding parasitic capacitance of the pad fixture. The maximum fT, measured at a gate/source voltage...
The changes in electrical properties induced by bending were reproducible in their response to further bending cycles. The changes in the gain profiles in the bent and unbent states are moderate, as illustrated by the data given in Fig. 2(c). These variations are much larger than those associated with repeated measurement at any given bend configuration within this range. The inset shows the variation in the normalized gain with hundreds of bending cycles, indicating little evidence for fatigue.

Using similar inverters, we fabricated five-stage ring oscillators. Figure 3(a) provides optical images of oscillators on a PI substrate, and an equivalent circuit diagram. The $L_c$ and $L_d$ values of these transistors are 4 and 2.5 μm, respectively. Figure 3(b) shows the measured wave form at a supply voltage $V_{DD}$ of 4 V. This response shows a frequency of 8.1 MHz, corresponding to a stage delay of 12 ns. The frequency stabilized quickly (less than a fraction of a second) after the supply voltage was applied. The operating voltages are much lower than the 20–45 V and 10–15 V reported for ring oscillators fabricated using organic transistors and poly-crystalline Si on flexible substrates, respectively, as well as the 43 V value reported for systems that use nanowire transistors on rigid glass substrates. Additional improvements in device design, such as reduction of contact overlap and channel length, should lead to significantly higher oscillation frequencies. We performed bending tests on the ring oscillators. Figure 3(c) shows some results that indicate frequencies of 8.1 MHz in the unbent state (red), 8.5 MHz at 0.23% tensile strain (green), and 7.3 MHz at 0.23% compressive strain (blue). The change in the operating frequency with strain might result from slight strain-induced changes in the mobility of the silicon in combination with other variations in different parts of the device. The results, then, indicate that although the devices can operate at reasonably high levels of bending-induced strain, subtle variations in device properties can lead to changes in circuit operation, in this case at the ~10% –20% level for the oscillation frequency.

The circuit operation ceases at bending strains that are far below those needed to cause complete failure of the individual transistors or any of the inverters. At the circuit level, even slight mismatches in gain profiles of any of the five stages induced by bending will render the oscillator inoperable. There is, then, a fundamental difference of the failure mechanisms of the transistors or inverters (i.e., cracking or bending).
delamination of critical material layers) and failure of the ring oscillators (i.e., device property changes sufficient to prevent circuit oscillation). For circuits that must operate in conditions that involve bending, and especially those that require more delicate matching of device properties than the simple ring oscillators described here, these variations should be considered in the mechanical and electrical designs.

In some cases, the circuits do not have to operate during bending, but rather they must be bendable for installation. An example is a structural health monitor, in which the flexible strains must be considered in the electrical and/or mechanical aspects of device/circuit design.

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FIG. 4. (Color online) (a) Image of an array of differential amplifiers on a PI substrate (top), magnified view of a single amplifier (bottom left), and circuit diagram (bottom right) [red: current source (three transistors with $L_c=30$ $\mu$m and $W=80$ $\mu$m), green: current mirror (two transistors with $L_c=40$ $\mu$m, $W=120$ $\mu$m and $L_c=20$ $\mu$m, $W=120$ $\mu$m), blue: differential pair (two transistors with $L_c=30$ $\mu$m and $W=180$ $\mu$m), cyan: load (two transistors with $L_c=40$ $\mu$m and $W=80$ $\mu$m)]. The $L_c$ values of these transistors are $15$ $\mu$m. (b) The time variation of the input and output signals (black: $V_{IN}$ and red: $V_{OUT}$). (c) Frequency response of a representative differential amplifier with an input signal of 500 mV PP.