Spin on dopants for high-performance single-crystal silicon transistors on flexible plastic substrates


University of Illinois at Urbana-Champaign, Department of Materials Science and Engineering, Department of Chemistry, Beckman Institute and Frederick Seitz Materials Research Laboratory, Urbana, Illinois 61801

(Received 29 December 2004; accepted 8 February 2005; published online 23 March 2005)

Free-standing micro/nanoelements of single-crystal silicon with integrated doped regions for contacts provide a type of material that can be printed onto low-temperature device substrates, such as plastic, for high-performance mechanically flexible thin-film transistors (TFTs). We present simple approaches for fabricating collections of these elements, which we refer to as microstructured silicon (μs-Si), and for using spin-on dopants to introduce doped regions in them. Electrical and mechanical measurements of TFTs formed on plastic substrates with this doped μs-Si indicate excellent performance. These and other characteristics make the material potentially useful for emerging large area, flexible ‘macroelectronic’ devices. © 2005 American Institute of Physics. [DOI: 10.1063/1.1894611]

Large area, mechanically flexible electronic systems, known as macroelectronics, are attractive for a range of applications in consumer electronics, sensors, medical devices, and other areas. A variety of organic, inorganic, and organic/inorganic hybrid materials have been explored as semiconductors for these systems. We recently demonstrated a “top-down” technology for generating single crystal silicon micro/nanoelements (wires, ribbons, platelets, etc.), which we refer to collectively as microstructured silicon, μs-Si that can be printed onto plastic substrates for high performance thin film transistors. The same strategy can be used with other important semiconductors, such as GaAs, InP, GaN, etc.

One of the key characteristics of this approach is its use of high quality, wafer-based sources of the semiconductor, which are grown and processed separately from the plastic device substrate. Here we show that it is possible not only to grow but also to selectively contact doped the semiconductor in steps that are performed independently from the low temperature substrates. We demonstrate, in particular, that spin on doping procedures performed at the wafer level can yield μs-Si with integrated doped regions. Electrical and mechanical characterization of transistors formed on plastic substrates with these materials illustrates the good performance and excellent bendability that can be achieved.

Figure 1(a) presents schematically the fabrication process for μs-Si transistors with doped source (S) and drain (D) contacts on PET substrates. The approach uses a solution processable spin-on dopant (SOD) to dope selected regions of the top silicon layer of a silicon-on-insulator wafer (SOI; Soitec unibond with a 100 nm top Si layer and 200 nm buried oxide). This doped SOI provides the source of silicon for the μs-Si. To produce this μs-Si, we spin cast a spin-on glass (SOG) solution (Filmtronic) onto a SOI wafer and exposed it to rapid thermal annealing (RTA) at 700 °C for 4 min to form a uniform film (300 nm thickness). Etching [6:1 buffered oxide etchant (BOE) for 50 s] through a lithographically patterned layer of photoresist (Shipley 1805) opened source and drain windows in the SOG. After stripping the resist, we uniformly deposited a phosphorus containing SOD (Filmtronic) by spin casting. RTA at 950 °C for 5 s caused the phosphorus from the SOD to diffuse through the lithographically defined openings in the SOG and into the underlying silicon. The SOG blocked diffusion in the other areas. The wafer was rapidly cooled to room temperature, immersed in BOE for 90 s to remove both the SOG and SOD and then thoroughly washed with DI water to complete the doping process.

We used techniques described previously to create the μs-Si and print it onto plastic substrates of PET coated with indium tin oxide (ITO; 100 nm, gate electrode) and epoxy

![Schematic illustration of process steps for fabricating flexible single crystal silicon transistors with doped contacts on plastic substrates. A spin-on dopant (SOD) provides the phosphorus dopant. A spin-on glass (SOG) serves as a mask to control where dopant diffuses into the silicon. After doping, the silicon is removed from the wafer and transfer printed onto a plastic substrate where device fabrication is completed; (b) optical images of an array of devices on a plastic substrate.](image-url)
plastic. The linear current and fitting of the resistance between two contact pads,  

\[ R_c \]

de the resistance for uniform, highly doped \( \mu \)-Si thin film. The intercept of a linear fit to these data gives a contact resistance. Inset shows the test structures for evaluating the contact resistance; (b) phosphorus concentration in a silicon film with patterned doping, as evaluated by TOF-SIMS.

We estimated the doping levels and the contact resistances using a standard transmission line model (TLM). In particular, we measured resistances between Ti contact pads with separations \( L \) and 50 and 100 \( \mu m \) and widths \( W \) of 200 \( \mu m \) [inset in Fig. 2(a)] on uniformly doped \( \mu \)-Si on plastic. The linear current \( (I) \) vs. voltage \( (V) \) curves (not shown) indicate that the contacts are ohmic and that the doping level is high. The dependence of the resistance on \( L \) can be described by

\[ R_{total} = 2R_c + (R_s/W)L \]

where \( R_{total} = (V/I) \) is the resistance between two contact pads, \( R_c \) is the contact resistance, and \( R_s \) is the sheet resistance. Figure 2(a) plots the normalized resistance, \( R_{total}W \), as a function of \( L \). Linear fitting of \( R_{total}W \) gives \( R_c = 228 \pm 5 \) \( \Omega/\mu m \), and \( R_sW \sim 1.7 \pm 0.05 \) \( \Omega cm \). The value of normalized contact resistance \( R_cW \) is more than an order of magnitude lower than what we observed for undoped \( \mu \)-Si processed in a similar manner. The resistivity is about \( 2.3 \times 10^{-3} \) \( \Omega cm \), which corresponds to a doping level of \( 10^{19} \text{cm}^{-3} \) if we assume, for simplicity, that the doping is uniform through the 100 nm \( \mu \)-Si film. As illustrated by the time-of-flight secondary ion mass spectroscopy (TOF-SIMS) measurements in Fig. 2(b), the use of patterned SOG as a diffusion barrier (Fig. 1) localizes the dopants to desired regions in the silicon. In this image, the bright red color indicates high phosphorus concentration.

Figure 3 shows measurements of typical contact-doped \( \mu \)-Si transistors on an epoxy/ITO/PET substrate. Figure 3(a) plots the current–voltage characteristics of a device \( (L = 7 \mu m, W = 200 \mu m) \). The effective device mobility \( (\mu_{eff}) \) is \( \sim 240 \text{cm}^2/\text{V} \cdot \text{s} \) in the linear regime and \( \sim 120 \text{cm}^2/\text{V} \cdot \text{s} \) in the saturation regime, as determined by application of standard field-effect transistor models. Figure 2(b) shows transfer characteristics of devices with channel lengths between 2 and 97 \( \mu m \) and channel widths of 200 \( \mu m \). The ON to OFF current ratios in all cases are \( \sim 10^4 \). Figure 3(c) presents the resistance of the devices measured in ON state \( (R_{on}) \) at small drain voltages, and multiplied by \( W \), as a function of \( L \) at different gate voltages. Linear fits of \( R_{on}W \) vs. \( L \) at each gate voltage provide information about both intrinsic device mobility and contact resistance. In this simple model, \( R_{on} \) consists of the series addition of the channel resistance (which is proportional to \( L \)) and the combined contact resistance \( R_c \) associated with the source and drain electrodes. Figure 3(c) shows that \( R_{on} \), as determined from the intercepts of linear fitting, is negligible compared to channel resistance for all channel lengths evaluated. The inset shows the variation of sheet conductance, as determined from the reciprocal of the slope of linear fitting in Fig. 3(c), with gate voltage. The linear fit to these data gives an intrinsic device mobility of \( \sim 270 \text{cm}^2/\text{V} \cdot \text{s} \), and an intrinsic threshold voltage of \( \sim 2 \text{V} \).

Figure 3(d) compares the effective mobilities, \( \mu_{eff} \), of undoped and contact-doped \( \mu \)-Si transistors evaluated directly from transfer characteristics measured in the linear regime (i.e., contact effects are not subtracted). For the undoped devices, \( \mu_{eff} \) decreases rapidly from 200 to 50 \text{cm}^2/\text{V} \cdot \text{s} \) with decreasing the channel length \( L \) from 100 to 5 \( \mu m \). The contacts begin to dominate device behavior at channel lengths below \( \sim 50 \mu m \). In the contact doped case, the mobilities are around \( 270 \text{cm}^2/\text{V} \cdot \text{s} \), with \( < 10\% \) variation with channel length over this range, which is in consistent with the intrinsic device mobility determined from inset of Fig. 3(c). These data provide additional evidence that these devices show negligible effects of contact resistance. We note that, in addition to the different mobilities, the devices with doped contacts are more stable, more...
uniform in their properties and less sensitive to processing conditions than those with undoped contacts.

Mechanical flexibility is an important characteristic of devices of this type. We performed systematic bending tests on the contact-doped μ-Si transistors, with bending directions that place the devices in compression and in tension. We also carried out some fatigue tests. The details of the experimental setup can be found elsewhere. The change in the properties of the devices was observed; after 350 cycles, the normalized effective mobility and the on/off ratio change by less than 20%.

In summary, this letter demonstrates a spin-on dopant process for contact-doped single crystal silicon transistors on plastic substrates. Scaling analysis indicates that this process yields devices that are not contact limited, which creates the possibility for high frequency silicon devices on plastic substrates. This feature, combined with the remarkably good mechanical flexibility and fatigue stability of the devices, make this contact doped μ-Si approach a promising potential route to flexible macroelectronic systems.

The work was partially supported by the Defense Advanced Projects Agency under Contract No. F8650-04-C-710 and the U.S. Department of Energy under Grant No. DEFG02-91-ER45439. Devices were fabricated using the Frederick Seitz Materials Research Laboratory facilities and characterized in the Center for Microanalysis of Materials, University of Illinois, which is partially supported by the U.S. Department of Energy under Grant No. DEFG02-91-ER45439.

For reviews and references, see Thin Film Transistors, edited by C. R. Kagan and P. Andry (Dekker, New York, 2003).

4. For reviews and references, see Thin Film Transistors, edited by C. R. Kagan and P. Andry (Dekker, New York, 2003).
8. We note that the active interface of the device might lie at the interface between a native SiO₂ layer and the Si, rather than between the Si and the epoxy. In this case, the dielectric is a composite, consisting of the native SiO₂ and the epoxy. The details represent topics of current study.