Scavenging of gases. In addition to the particles, numerous trace gases are present in the atmosphere (Table 2). Gases are taken up by drops because they are more or less soluble. The maximum amount of a gas that can be taken up into water is a function of the Henry’s law coefficient \( H \), which gives the ratio of the concentration of the gas in water (mol L\(^{-1}\)) with respect to the concentration in air (atm).

When the gas is very soluble (for example, HNO\(_3\), where \( H = 2.1 \times 10^5 \) mol L\(^{-1}\) atm\(^{-1}\) at 298K), the gas is very efficiently scavenged. When the gas is almost insoluble (for example O\(_3\), where \( H = 9.4 \times 10^{-3} \) mol L\(^{-1}\) atm\(^{-1}\) at 298K), the gas mostly remains in the air. Henry’s law describes an equilibrium between the concentration in the air and the liquid.

Once in the liquid phase, most gases are destroyed by chemical reactions, and thus an equilibrium is never achieved. Consequently, more and more gas can be taken up into the cloud drops. Only the drop lifetime (maximum of 30 min) will limit the gas scavenging.

Summary of cloud processes. Atmospheric pollution is made of aerosol particles and trace gases. Both are taken up into cloud hydrometeors during the lifetime of a cloud. The processes acting inside the clouds are called “in-cloud scavenging” or “wash out.” The dominating processes are the nucleation of drops on existing aerosol particles. This transfers almost 90% of the particulate pollution mass inside the cloud volume in the liquid phase. In addition, the liquid drops take up gases according to their solubility and the ongoing chemical destruction in the liquid phase. Once temperature decreases significantly below 0°C (32°F), the drops freeze. Once frozen, the uptake of particles and gases is significantly reduced, as the solid crystals have difficulty retaining the colliding aerosol particles and dissolving gases.

Through collision, the hydrometeors can become sufficiently large and heavy to fall against the prevailing updrafts toward the ground. During the time of fall, the big drops continue to take up particles and gases. This is called “below cloud scavenging” or “rain out.”

Globally, it is estimated that below-cloud scavenging contributes around one-third of the pollution mass in the rain, while the remaining two-thirds is taken up inside the cloud. Roughly the same ratio seems to exist in ground precipitation between the pollution mass that was contributed by the particulate pollution mass (two-thirds) and the gaseous pollution mass (one-third). However, these numbers just represent orders of magnitude, and will be different for the different chemical components that the particles and gases are made of. Also, these numbers will be influenced by the presence of the ice phase, the size of the cloud, and the intensity of precipitation. All these scavenging processes contribute to the cleaning process of the atmosphere and a deposition of pollution onto the ground.

Since only half of the liquid water of the cloud precipitates and the rest evaporates, pollution in the cloud hydrometeors is released back into the air. This pollution mass is also significantly altered with respect to the initial air—the particles are generally larger and have more chemical species attached to them due to nonvolatilized gases. Also, the trace-gas concentration is altered. Thus, precipitation scavenging also influences air pollution and atmospheric chemistry.

For background information see AEROSOL; AIR POLLUTION; ATMOSPHERE; ATMOSPHERIC CHEMISTRY; CLOUD; CLOUD PHYSICS; PRECIPITATION (METEOROLOGY) in the McGraw-Hill Encyclopedia of Science & Technology.

Andrea I. Flossmann

amorphous silicon. The low degree of crystallinity associated with these materials and the unfavorable nature of charge transport in them (for example, hopping mode as opposed to bandlike) results in relatively low performance and in some cases uncertain reliability and reproducibility, both of which limit their applications. Recently, a completely different approach has been explored, whereby high-quality single-crystalline inorganic semiconductors are directly printing onto a plastic substrates, followed by depositing and patterning other materials at relatively low temperatures (less than 250°C) to construct flexible transistors and circuits, with performances approaching that of similarly scaled wafer-based systems.

**Fabrication of semiconductor microstructures.**

Single-crystalline micro/nanostructures of semiconductors can be fabricated from conventional wafers of these materials through “top-down” approaches in which lithographic patterning and etching create the desired structures from the near-surface regions of the wafers. Semiconductor structures generated in this manner inherit the high quality of the original wafers in terms of well-controlled doping type, carrier concentration, dimensions, and crystallinity, which in turn enables excellent electrical properties in devices using them. Two etching strategies have been used to produce these kinds of structures (Fig. 1). The most straightforward approach involves isotropic etching of sacrificial layers of multiple-layered wafers to release thin semiconductor structures (Fig. 1a).

Typical examples include Si ribbons generated from silicon-on-insulator (SOI) wafers and GaAs ribbons from GaAs wafers with epitaxial layers of AlAs and GaAs (top surfaces), where lithographic steps are followed by removal of SiO2 and AlAs, respectively, to release thin semiconductor ribbons. Figure 1b shows a scanning electron microscope image of GaAs ribbons with thicknesses of 270 nm, widths of 5 μm, and lengths of up to several centimeters, clearly showing the mechanical flexibility of these ribbons.

In another approach, similar lithographic steps, followed by anisotropic etching of bulk wafers along certain crystallographic planes, generates ribbons/wires from standard wafers. Figure 1c depicts a process for generating Si ribbons from a (111) Si wafer. The first step defines shallow trenches with side walls terminated by (110) planes by lithography and reactive ion etching. Coating the top surfaces of the plateaus and parts of the sidewalls of the trenches with thin resists of SiO2, Si3N4, and Au, followed by etching in hot potassium hydroxide (KOH) solution generates thin ribbons of Si. Figure 1d presents a scanning electron microscope image of ribbons fabricated by this process. In a related but simpler process, anisotropic etching that yields reverse mesas

---

**Fig. 1. Fabrication procedures (a, c, e) which involve the combined use of lithography and wet chemical etching to generate micro/nanostructures of single-crystalline inorganic semiconductors. Scanning electron microscope images of structures fabricated using these approaches: (b) GaAs ribbons, (d) Si ribbons, and (f) GaAs wires with triangular cross sections.**
Transfer printing of micro/nanostructures. Micro/nanostructures fabricated via the procedures of Fig. 1 can retain the positional and orientational order defined by the lithography by using designs that leave these elements anchored to the wafer at their ends. Ordered wires/ribbons produced in this manner can be transfer-printed onto substrates, such as plastic sheets, using elastomeric [polydimethylsiloxane (PDMS)] stamps as transfer elements. Figure 2 shows the major steps of the printing process. First, laminating a flat PDMS slab on the surface of a wafer with patterned patches of wires/ribbons generates a conformal contact. Generalized adhesion forces (or strong chemical bonds, with appropriately designed surface chemistries) bond the semiconductor micro/nanostructures to the surface of the PDMS (step i). Peeling the PDMS stamp away from the wafer transfers all of the micro/nanostructures to the stamp (step ii). Placing this “inked” stamp against a plastic substrate coated with a thin layer of adhesive (such as epoxy resins or photocurable polymers), activating the adhesive (curing the polymer), and then peeling back the stamp completes the printing (step iii). In a related approach, control of peel rate enables transfer without adhesives. The printed arrays of semiconductor micro/nanostructures can be processed into thin-film transistors (TFTs) through traditional photolithography and deposition of other materials that are compatible with the plastic substrate. If high-temperature processing, such as annealing of ohmic contacts for GaAs, doping of Si, and growth of thermal oxides on Si, is required, the related steps can be carried out on the wafer before transfer. By repetitive printing in a step and repeat fashion, it is possible to process devices over areas on the plastic substrate that are much larger than the size of the wafer (Fig. 2b). A patterned PDMS stamp can pick up ribs/wires at selected areas by spatially registering the posts; the remaining micro/nanostructures on the wafer can be printed in subsequent step.

Examples and electrical characterization of flexible TFTs. The printed arrays of wires/ribbons can serve as active materials for high-performance electronic devices. Figure 3a shows an optical image of a 25-μm-thick polyimide sheet, covered with an array of metal oxide semiconductor field-effect transistors (MOSFETs) fabricated with 290-nm-thick Si ribbons with contact doped regions. (Note their flexibility.) The adhesive layer used is polyamic acid, a liquid that can be converted into electronic grade polyimide by baking. The dielectric material is SiO₂ formed by low-temperature (about 250 °C) plasma-enhanced chemical vapor deposition (PECVD). Source, drain, and gate electrodes use Cr/Au (5/100 nm) deposited by electron-beam evaporation. Figure 3 shows the geometry of the devices. These transistors exhibit electrical behavior similar to that of typical MOSFETs fabricated on wafers. Figure 3d shows the dependence of current flow from source to drain (Iₑₒ) of a transistor with a channel length (Lₚ) of 9 μm, channel overlap distance (Lₒ) of 5.5 μm, and channel width (Wₑ) of 200 μm on the drain voltage (Vₑₒ) at different...
gate voltages ($V_{GS}$). Figure 3e shows the transfer curves from devices with different channel lengths. The linear regime mobilities extracted from this type of device are as high as about 500 cm$^2$/V·s, which are higher than those possible with other approaches. Figure 3f shows the result of microwave measurement over a transistor with $L_c = 2 \mu$m, $L_o = 1.5 \mu$m, and $W_c = 200 \mu$m. The unity current gain frequency ($f_T$) is about 500 MHz for this device. This frequency can be increased by reducing $L_c$ and/or $L_o$, but this approach is not attractive for many macroelectronic systems because it requires high-resolution
lithography, which can be difficult to achieve in a cost-effective manner on large-area plastic substrates.

By contrast, metal-semiconductor field-effect transistor (MESFET) devices made of GaAs wires can offer high speeds even with coarse patterning resolution and limited capacity for overlay registration, the latter of which is of particular advantage for plastic substrates since they often do not show good dimensional stability over large areas. MESFETs (as images shown in the insets of Fig. 3g) with $L_e$ of 50 $\mu$m, $W_e$ of 150 $\mu$m, and gate length of 2 $\mu$m fabricated with GaAs wires (width of about 2 $\mu$m) integrated with ohmic stripes, exhibit $f_1$ in gigahertz regime, that is, 1.55 GHz (Fig. 3g). These MESFETs use flexible poly(ethylene terephthalate) [polyester] substrates with thin polyurethane adhesive layers. This level of high-frequency operation indicates a potentially promising pathway to large active antennas operating at ultrahigh frequencies.

**Mechanical characterization of TFTs.** Good bendability is an important characteristic of many of the envisioned applications. The flexibility of transistors fabricated with single-crystalline micro/nanostructures was systematically evaluated by squeezing the plastic substrates with specially designed mechanical stages to generate concave (compressive strains on top device surface) and convex surfaces (tensile strains) [Fig. 4a]. Figure 4b shows the variation of linear regime device mobility in a silicon transistor, normalized by the value in the unbent state $\mu_{0_{\text{eff}}}$ with bending radius and surface strain. The results indicate only small changes in device performance in this range of strains. Repetitive bending for many cycles (fatigue studies) confirm the robustness and durability of these devices (Fig. 4c).

**Integration of flexible TFTs into complex circuits.** High-performance individual transistors of the type described above can be integrated into circuits with desired functionalities for particular applications. For example, integrating five Si-ribbon-based n-MOSFETs with channel widths of 200 $\mu$m (serving as drivers) and five devices with channel widths of 30 $\mu$m (serving as loads) forms a five-stage ring oscillator. $L_e$ and $L_o$ of all transistors are 4 and 2 $\mu$m, respectively. Figure 5a and b show an optical image of a typical and its equivalent circuit. Figure 5c presents the measured waveform for the ring oscillator shown in Fig. 5a at supply voltage $V_{dd} = 4$ V. The circuit exhibits a maximal oscillation frequency of 8.2 MHz, corresponding to a stage delay of 12 ns. The oscillation speed of circuits can be further increased by reducing the contact overlaps and channel lengths.

**Outlook.** Flexible transistors that show high performance on plastic substrates can be achieved using printed single-crystalline inorganic micro/nanostructures of various semiconductors, such as Si, GaAs, and GaN, generated from high-quality single-crystal bulk wafers. Electrical and mechanical measurements indicate that the devices provide a promising class of building block for flexible macroelectronic applications. Preliminary results imply that individual TFTs of this kind can be integrated into complex circuits with appropriate functionalities for particular applications. Further improvement in device design and processing steps to increase performance, particularly in terms of operation speed, as well as improved device yields represent current directions for research in this field.

[Acknowledgment: The work was partially supported by the Defense Advanced Projects Agency under Contract No. F8650-04-C-7101 and by the U.S.
Reducing human error in medicine

Human error in medicine contributes to adverse events that threaten patient safety. Certain errors tend to recur across adverse events in health care, reflecting unmet perceptual, cognitive, and behavioral needs as users interact with systems to accomplish patient care goals. For example, slips such as overdosing patients result from inputting the wrong number into infusion pumps or misreading medication orders because critical information is not highlighted or similar symbols are confused on the interface or in the order.

Human factors researchers have made important contributions to patient safety by raising awareness of the role of preventable medical errors in adverse events, and developing and evaluating approaches to mitigating these errors. This is due in part to analytical tools (for example, task analysis) that identify user needs and the extent to which they are met by health care systems.

Framework for analyzing error. The 1999 Institute of Medicine report, To Err Is Human: Building a Safer Health System, estimated that more than 98,000 deaths per year are attributable to medical error. As in other high-risk professions, such as aviation, it is misleading to equate human error with human fault. For example, outcomes labeled adverse events in medicine may be viewed as “bad” only in hindsight. Given the uncertain nature of patients’ responses to treatment, it is likely that many adverse events occur in spite of appropriate diagnosis and treatment.

A definition of human error remains elusive. According to one definition, it is substandard human performance that should have been recognized by the practitioner as substandard at the time it occurred.

Progress in reducing errors depends on frameworks that specify methods for measuring and analyzing error and guiding design and training interventions. D. G. Morrow and coworkers have combined the error taxonomy of psychologist James Reason with an information-processing stage model. Events are detected depending on the extent that they are attended to, and then interpreted (for example, understanding and integrating multiple symptoms in diagnosis). Such operations require knowledge stored

References:


Fig. 5. Five-stage ring oscillator fabricated with Si-ribbon-based transistors. (a) Optical image, (b) equivalent circuit, and (c) output waveform.