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Gutenberg + nanotechnology = printable electronics

(*Nanowerk Spotlight*) Nanoelectronics devices often are made by integrating dissimilar semiconductors and various other disparate materials into one heterogeneous single primary modes of combining these materials - mechanical bonding and epitaxial growth place stringent requirements on the ultimate scale or constituent materials of circuits. bonding, there is a limited ability to scale to large areas (i.e., larger than the wafers) (few stacking layers; incompatibility with unusual materials (such as nanostructured n temperature materials and substrates; challenging fabrication and alignment for the electrical interconnects; demanding requirements for planar bonding surfaces; and bonding that can occur from mechanical strains generated by differential thermal expansion of disparate materials. Epitaxy avoids some of these problems but places severe restrictions on type of materials that can be grown. Using a process akin to the printing press, researchers managed to bypass the need for epitaxial growth or wafer bonding to integrate wide range of dissimilar semiconducting nanomaterials onto substrates for the purpose of constructing three dimensional electronics.

Printed semiconductor nanomaterials provide new approaches to 3D heterogeneous systems that could be important in various fields of applications such as microfluidic integrated electronics, chemical and biological sensor systems that incorporate unusual conventional silicon-based electronics, and photonic and optoelectronic systems that use emitters and detectors of compound semiconductor with silicon drive electronics or nanoelectromechanical structures. Furthermore, the compatibility of this approach with thin substrates may create additional opportunities for devices that have unusual form factors flexibility as key features.

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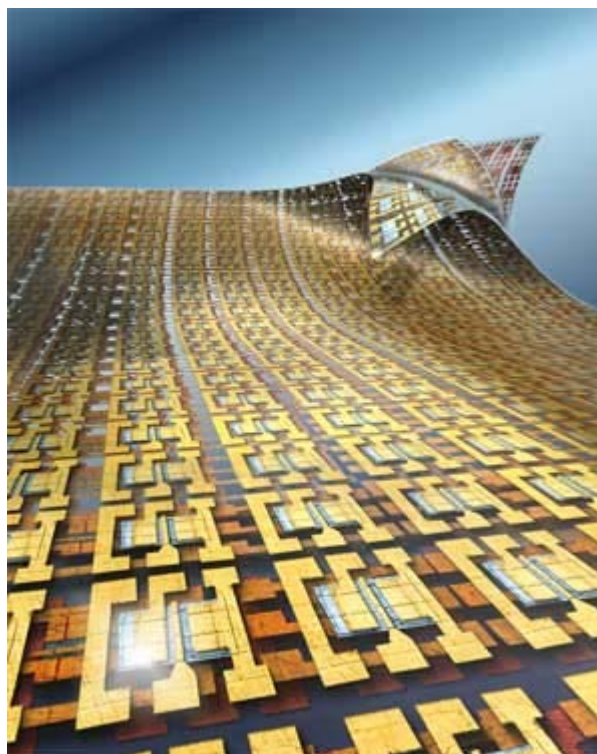
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*illustration based on confocal images of actual three layer stacks of transistors that use
 ribbons of silicon for the semiconductor and a thin sheet of polyimide for the substrate
 research group)*

"Our approach, the combined use of semiconductor nanomaterials and printing technology to form quality electronics to be formed on diverse substrates, including nonplanar surfaces and flexible sheets" [John A. Rogers](#) tells Nanowerk. "These capabilities, in particular the ability to use a wide range of component materials, all lie well outside of the range of things that can be achieved with conventional wafer based approaches to electronics."

Rogers, a professor of chemistry, materials science and engineering at the University of Illinois at Urbana-Champaign, and his research group are trying to develop approaches that enable "high performance electronics anywhere", i.e. they would like to extend semiconductor device fabrication to substrates other than the semiconductor wafer.

"Our goal is to invent methods that can allow interesting applications which cannot be achieved with conventional technologies, such as flexible displays, large area solar cells, conformable sensors, distributed structural and personal health monitors, curved surface imagers and other devices," says Rogers. "Our belief is that inorganic semiconductor nanomaterials, delivered to a target substrate using printing techniques, forms an attractive way to achieve devices of these types."

The recent results by Rogers' group show how dissimilar single-crystal inorganic semiconductors (such as micro- and nanoscale wires and ribbons of GaN, Si, and GaAs) can be combined and also with other classes of nanomaterials (such as single-walled carbon nanotubes) using the use of a scalable and deterministic printing method to yield complex, heterogeneous electronic systems in 2D or 3D layouts.

Specifically, the nanoscale semiconductor components are first fabricated, each on its own substrate, through standard lithographic procedures, with ohmic contacts formed by annealing. These components are then lifted from the source substrate by gentle van der Waals adhesion with an 'inking pad' made of polydimethylsiloxane, and then 'stamped' onto the target substrate such as a sheet of polyimide.

After some additional processing – including deposition and patterning of gate dielectrics and interconnects – the transfer printing and device fabrication steps can be repeated.

spin-coating a new prepolymer interlayer on top of the previously completed circuit le

Rogers points out that this fabrication approach has several important features:

First, all of the processing on the device substrate occurs at low temperatures, thereby avoiding differential thermal expansion and shrinkage effects that can result in unwanted deformation of multilayer stacked systems. This operation also enables the use of low-temperature processing and interlayer materials, and it helps to ensure that underlying circuit layers are not damaged by the processing of overlying devices.

Second, the method is applicable to broad classes of semiconductor nanomaterials, including materials such as SWNTs.

Third, the soft stamps enable nondestructive contacts with underlying device layers; together with the ultrathin semiconductor materials, they can also tolerate surfaces that have irregular topography.

Fourth, the ultrathin device geometries and interlayers allow easy formation of layer-to-layer interconnects by direct metallization over the device structure. These features overcome the disadvantages of conventional approaches.

The researchers demonstrated the capabilities of their printing process by fabricating stacks of high-performance metal oxide semiconductor field-effect transistors (MOSFETs), heterojunction bipolar transistors (HBTs), thin-film transistors (TFTs), photodiodes, and other components integrated into device arrays, logic gates, and actively addressable photodetectors on flexible plastic substrates.

"We are now working to make these kinds of approaches realistic methods for manufacturing," says Rogers. "We focus on (1) the development of tooling to automate the process, and (2) the development of devices, i.e. electronic eye imagers, large area solar cells, and flexible displays, that demonstrate the utility of these approaches."

These findings have been published in a recent paper in the December 15, 2006 issue of *Nature* ("Heterogeneous Three-Dimensional Electronics by Use of Printed Semiconductor Nanomaterials")

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