A virtual substrate opens path to oxide films on silicon for application in 5G, MEMS, sensors and quantum computation

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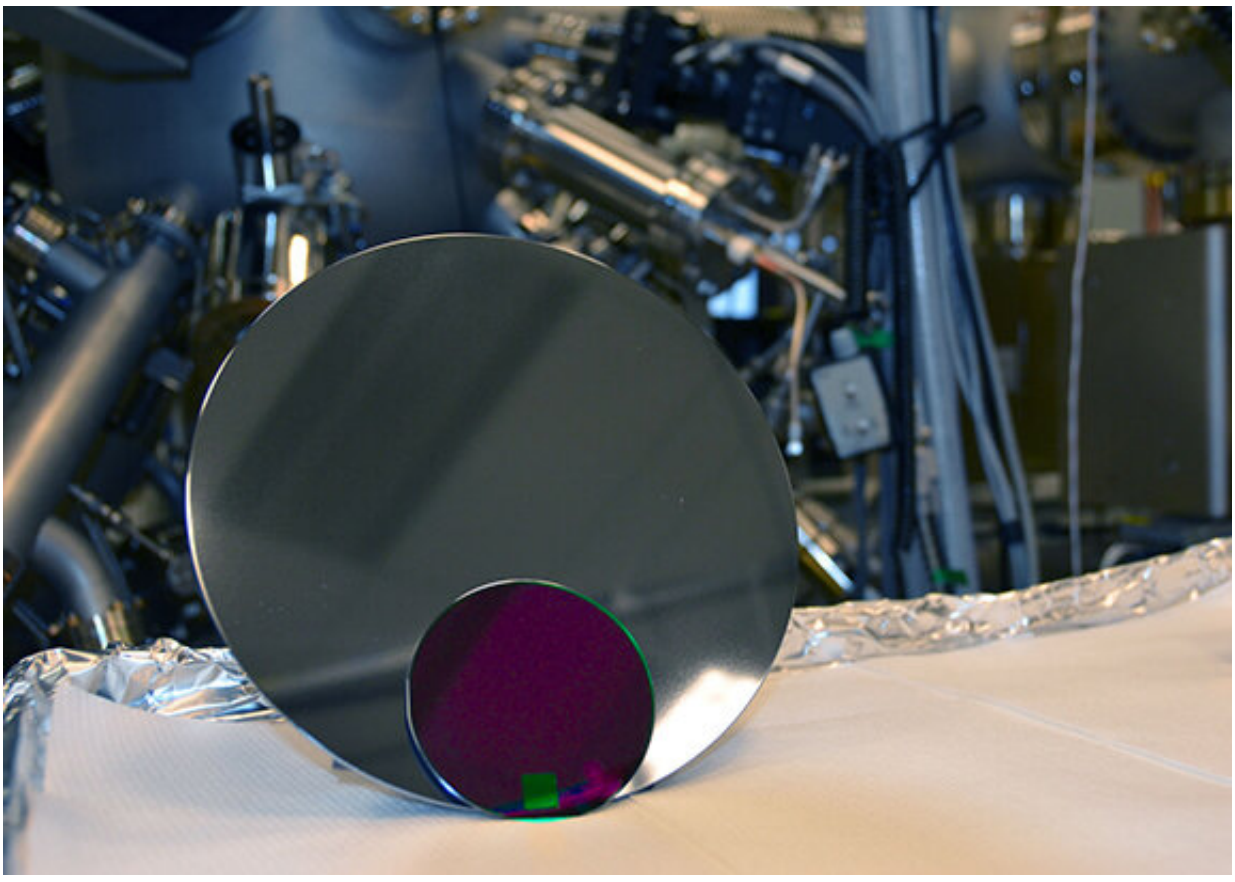

A 10 x 10mm chip (green) represents the conventional bulk oxide substrate. A 3-inch virtual oxide substrate on silicon(purple) is now possible. The 8-inch silicon wafer (silver) is projected for industry scale up. In the background is a hybrid molecular beam epitaxy system. Credit: MRI/Penn State

Proof that a new ability to grow thin films of an important class of materials called complex oxides will, for the first time, make these materials commercially feasible, according to Penn State materials scientists.

Complex oxides are crystals with a composition that typically consists of oxygen and at least two other, different elements. In their crystalline form and depending on the combination of elements, complex oxides display a tremendous range of properties.

"Complex oxides are sometimes called functional materials, because they are literally good for everything," says Roman Engel-Herbert, associate professor of materials science and engineering, chemistry and physics, Penn State.

The particular complex oxides his group is targeting are called perovskite oxides. The crystal structure—the arrangement of atoms—of this material contains two positively charged ions that can be substituted by nearly all elements of the periodic table forming positively charged ions. Depending on which type of atoms are substituted, the researchers are able to get whichever properties they are interested in, including magnetism, ferroelectricity, pyro- and piezoelectricity—the ability to sense and respond to heat and to turn electricity into mechanical motion or vice versa, and even superconductivity.

Until now, the ability to utilize these materials as thin films for electronics and sensors has been stymied by either a very slow rate of growth or a lack of stoichiometry control, i.e. keeping the amount of positively charged ions in the crystal in the right proportion. It is even more troublesome that so far no commercially viable integration strategy is found to combine these functional oxides with existing semiconductor technology in a scalable and commercially viable way.

"For industry to take advantage of the dramatic breakthroughs we have witnessed in this field of complex oxide research, we have to somehow integrate these thin films into devices using technologies that are compatible with existing industrial manufacturing processes," Engel-Herbert says. "To do that you not only need the right substrate on which you can grow the film, you also need to make sure that substrates are large enough to translate technology to industry scale. While such substrates do not exist (yet), now there is a way forward to bridge this gap."

To solve this problem, Engel-Herbert's group grows thick layers of complex oxides on top of a silicon wafer. This thick layer, sometimes referred to as a 'virtual substrate' is structurally and chemically compatible with the targeted complex oxide thin film layer, thus mimicking the function of a real bulk oxide substrate. This materials strategy not only requires precise control of growth conditions to ensure a structurally perfect virtual substrate that can serve as a

platform to integrate functional oxide films directly on silicon, but also sufficiently fast growth rates. This method, although it is well established in the field of semiconductor science, has never been applied to complex oxides. The main barrier to its development has been the agonizingly slow growth rate for complex oxide thin films, about four angstroms per minute, or four tenths of a nanometer. At such slow rates growth of a sufficiently thick complex oxide layer would require five to six hours.

"If you want to use a virtual substrate instead of a conventional bulk single crystal substrate, you need orders of magnitude higher growth rates. Our breakthrough shows that we can now cut this time down from several hours to a couple of minutes while maintaining perfect control over the quality of the material," Engel-Herbert says.

The group has successfully demonstrated growth rates of about two

angstroms per second. Their results further indicate that even higher growth rates are possible, paving the way towards a commercially viable integration strategy for this functional class of materials with silicon.

"So far only 3-inch silicon wafer were used, but this is only because our growth chamber in the lab is not laid out to handle larger Si wafer," he says. "There is no reason that this cannot be done on 10-inch commercial silicon wafers."

An additional benefit besides a much faster growth rate is a greatly reduced cost to produce oxide substrates. With prices a fraction of the cost for currently available bulk oxide substrates, researchers would benefit as well, leading to more complex oxide thin film experiments and therefore more rapid progress in this area of research. Since properties of functional complex oxides span a wide range, possible future technologies enabled by and benefitting from scalable complex oxide virtual substrates are widespread: from quantum computers based on superconducting qubits, sensors, actuators and Micro-Electro-Mechanical Systems (MEMS) all the way to frequency agile devices that are being considered for future broadcast frequency standards in 5G networks.

Additional authors on the paper, published online in *Nature Communications*, titled "Scaling growth rates for perovskite oxide virtual substrates on silicon," are Ph.D. student and lead author Jason Lapano, former postdoctoral scholar Matthew Brahlek, former graduate student Lei Zhang, current Ph.D. student Joseph Roth and current postdoctoral scholar Alexej Pogrebnyakov.

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