A substrate-blind platform for photonic integration

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A new technique using high-index glasses enables photonic device integration on substrates such as semiconductors, glasses, IR crystals, polymers, and graphene.

The integrated photonic devices used in imaging and sensing are usually built through multiple microfabrication steps. These may include film deposition, lithographic patterning, or etching on a substrate. The selected substrate stipulates the fabrication methods and processing compatibility requirements. For example, silicon photonics has long relied on standard CMOS processing technologies developed by computer chip makers, whereas inkjet printing offers a versatile integration route compatible with the thermal and mechanical characteristics of soft polymers. These substrate-specific constraints mean that photonic device design rules and fabrication protocols often cannot be transferred between different platforms. Consequently, photonic integration technologies on common substrates are well advanced, but their counterparts on unconventional materials are still in their infancy. Examples of these less commonly used bases include plastics, metals, and optical crystals, which potentially offer new functionalities for renewable energy, imaging, sensing, and display applications.

Colleagues and I aimed to transcend these limitations by developing ‘substrate-blind’ platform technology. Our approach enables photonic integration on a variety of unconventional materials and leverages a well-established knowledge base and technical know-how derived from semiconductor photonics. As a result, our technique may in future streamline component design and improve fabrication throughput and yield. Furthermore, such technology also leads to large degrees of freedom in photonic design without compromising device performance. For example, stacked multilayer structures with tailored dielectric permittivity profiles (where the material can be polarized by an external electric field) are pivotal to devices operating on slot enhancement (the field concentration effect in a thin, low-index layer or ‘slot’ between two high-index strips),\(^1\) photonic band gap effects,\(^2\) or metamaterials with hyperbolic optical dispersion.\(^3\) Conventionally, these structures are difficult to fabricate because they require complicated epitaxial growth (deposition of crystalline layer upon crystalline substrate), but our platform technology can readily produce them.

For the backbone materials of our platform, we chose transition metal oxides and high-index amorphous chalcogenide glasses (ChGs). The glasses have several unique features. Unlike crystalline semiconductors, they can tolerate deposition on virtually all relevant substrates without requiring epitaxial growth.

Figure 1. A mid-IR chalcogenide (ChG) glass microdisk resonator fabricated on calcium fluoroide (CaF\(_2\)) crystals using the ‘substrate-blind’ approach. (a) Top-view optical micrograph of the device. The inset shows part of the coupling region between the resonator and the bus waveguide. (b) Mid-IR transmission spectrum of the microdisk resonator. (c) The same spectrum near an optical resonance peak (the red box in b). Measured data was fitted by coupled mode theory, and the intrinsic quality factor is about \(4 \times 10^5\). \(k\): Coupling coefficient. \(R\): Reflection coefficient. \(Q_{in}\): Intrinsic quality factor.

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Furthermore, we perform the deposition at reduced temperatures (typically below 250°C), which is critical to integration on polymers and minimizes thermal stress. We can shape the glass films into functional photonic devices using standard UV lithography and plasma etching commonly adopted in semiconductor microfabrication, but we can also use molding and printing, which are compatible with organic polymer processing. The glasses have broadband (visible to longwave IR) optical transparency, and have almost infinite capacity for composition alloying and tailoring of their properties. As an example, we can continuously tune the glasses’ refractive indices from 2.0 to 3.5 to meet a diverse range of device design needs.

Previous work enabled high-performance glass-based optical devices integrated on substrates of semiconductor and glass, and here we extended the substrate-blind integration strategy by realizing photonic integration on three types of emerging substrate platforms: IR optical crystals (calcium fluoride, CaF$_2$), flexible polymer membranes, and 2D materials (graphene). We deposited the glasses on the substrates using thermal evaporation or solution derivation, and then patterned them using photolithography or direct nanoimprinting. We demonstrated the procedure in several photonic components, including waveguides, resonators, gratings, and photonic crystals, with outstanding optical performance. Microdisk resonators fabricated on mid-IR transparent CaF$_2$ crystals (see Figure 1) and flexible polymer substrates (see Figure 2) feature quality (Q) factors of up to $4 \times 10^5$ and $5 \times 10^5$ at wavelengths of 5.2μm and 1550nm, respectively, representing world records for planar mid-IR resonators and flexible resonator devices. One way to develop highly flexible photonic structures is by predicting the emergence of multiple neutral axes, or zero-strain planes in bent laminated structures, known as multineutral axis design. The flexible resonators also exhibit superior mechanical robustness and can sustain repeated bending down to submillimeter radii, with minimal optical performance degradation.

Our approach also enables fabrication of complex 3D photonic structures through straightforward sequential multilayer deposition and patterning. Figure 3 shows two examples of these. The first is a mid-IR slot waveguide consisting of a germanium-antimony-sulfur glass slot sandwiched between two germanium-arsenic-selenium-tellurium layers on a CaF$_2$ substrate. The second is a flexible woodpile photonic crystal embedded inside an epoxy polymer. Compared to conventional 3D stacking methods involving wafer bonding, nano-manipulation, ion implantation, or multi-step chemical mechanical polishing, our approach offers a simple and robust alternative for novel 3D photonic structure processing on different substrates.

In summary, we have demonstrated an array of glass-based photonic devices and validated their substrate-blind monolithic photonic integration capacity. Our next step involves expanding our material repertoire to incorporate new active materials.
and passive functionalities. As an example, hybrid integration of crystalline semiconductors by nanomembrane transfer or adhesive bonding has shown great promise for active optoelectronic integration. Ultimately, we envision that our multilayer substrate-blind integration technology will expedite the penetration of integrated photonic technologies into emerging arenas such as imaging, sensing, and manufacturing, where unconventional substrate platforms prevail.

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References