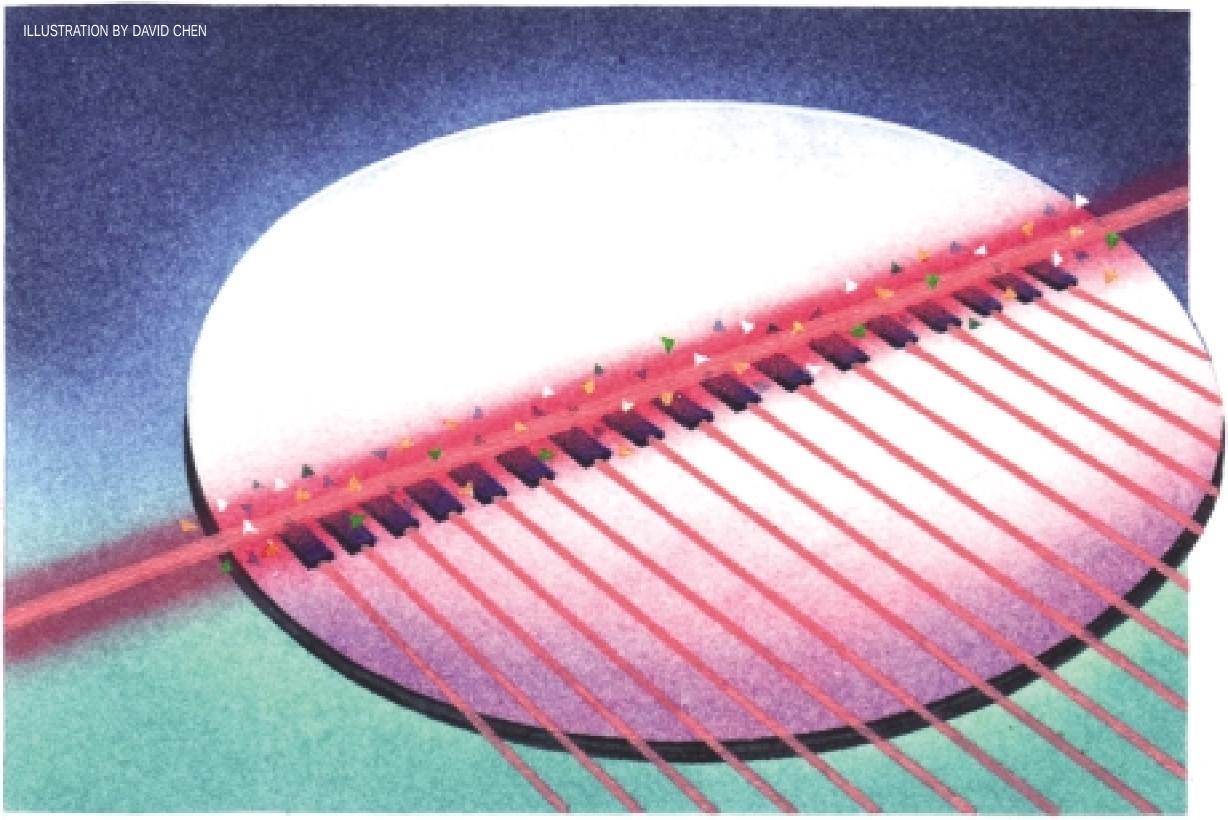

ILLUSTRATION BY DAVID CHEN

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Etching Advances

Replacing cleaved facets with etched facets produces improved lasers.

The evolution of electronics from discrete components to highly integrated, multifunction chips is well known. Previous attempts at photonic integration have been disappointing, however, especially for active components like lasers, modulators, and photodetectors. To meet cost and size requirements of future optical networks, integration of functions is becoming a necessity. Optimal integration technology must provide the desired functionality without excessive compromises in performance. It is also essential that the intrinsic yield per function be very high (above 95%), so that the cost of the integrated device is much lower than that of the equivalent assembly of individual functions.

Cornell University (Ithaca, NY) research is now yielding a fundamentally new way to manufacture integrated optoelectronic devices. The technique, undergoing further development by our own group, allows laser facets and other features on the chip to be defined through high-precision photolithography and etching rather than mechanical cleaving.[1] The process involves the use of chemically assisted ion-beam etching, a technique with extremely high directionality that is capable of forming mirror-smooth surfaces in a variety of semiconductor materials, including indium phosphide (InP), gallium arsenide (GaAs), and gallium nitride.

Etching Advantages

Etched facet technology (EFT) results in high uniformity and yield, and it enables the fabrication of novel microphotonic devices and structures. Etching is not dependent on the crystallographic plane of the semiconductor wafer, so devices can be optimally located. This design advantage also makes it possible to fabricate anti-reflection structures in place of conventional coatings. Most important, EFT eliminates the requirement for mechanical cleaving of facets, an inexact process that can degrade laser performance and decrease yield.

Because cleaving breaks off the end of the chip, monolithic integration past a cleaved facet is not possible. The fabrication of complete devices on the surface of the wafer by EFT allows the devices to be fully characterized while still in wafer form, facilitating low-cost automated testing. EFT also enables economical chip singulation using etched trenches or conventional dicing processes, since the optical facet is not created during the singulation process (see figure 1).

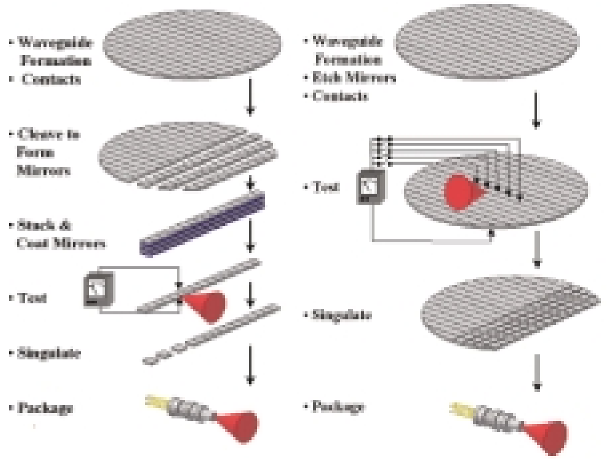

Figure 1 Conventional fabrication (left) forms laser facets with mechanical cleaving, which hampers testing. The etched facet process (right) allows wafer-level testing and simplifies singulation.

EFT allows flexible monolithic integration of optical functions on a single chip. Coupling between devices can be made in free space or using waveguides, and reflections can be controlled through geometrical structures like distributed Bragg reflectors (DBRs), as well as deposited thin films. We have demonstrated a variety of devices and functions, including single mode and ring lasers, high-speed and monitoring detectors, modulators, amplifiers, and passive waveguides. The etched devices are physically separated on the surface of the chip for optical isolation of greater than 40 dB and electrical isolation of greater than 100 MΩ. Ongoing reliability tests of unpackaged devices made with EFT at 90°C and 150°C have reached 12,000 and 9000 hours, respectively, showing robustness with respect to temperature and humidity.

The manufacture of single mode lasers typically requires multiple crystal regrowth steps, mechanical cleaving, and deposition of reflective coatings on the cleaved facets. A yield of 30% for standard distributed feedback (DFB) lasers is often considered good. The integration of multiple DFB lasers on a single chip is generally not economically viable.

Using the EFT approach, we have demonstrated performance similar to that of DFB lasers without the use of regrowth and optical coatings.[2] We have integrated etched structures like Fabry-Perot filters and DBRs in the laser cavity to achieve single-longitudinal-mode operation and wavelength control. Because these filtering and reflection control structures are fabricated from essentially the same material as the laser (InP), their properties track together with temperature, allowing the devices to operate at temperatures ranging from 0°C to 85°C without mode hopping.

The side-mode-suppression ratio typically exceeds 30 dB, which is lower than typical for DFBs but adequate for most data applications. The etched etalon filter used in our single mode design has broader spectral characteristics than the gratings used in a typical DFB laser, which makes it less effective at filtering off-peak wavelengths. The EFT approach eliminates the need for costly regrowth, however, which can decrease yield.

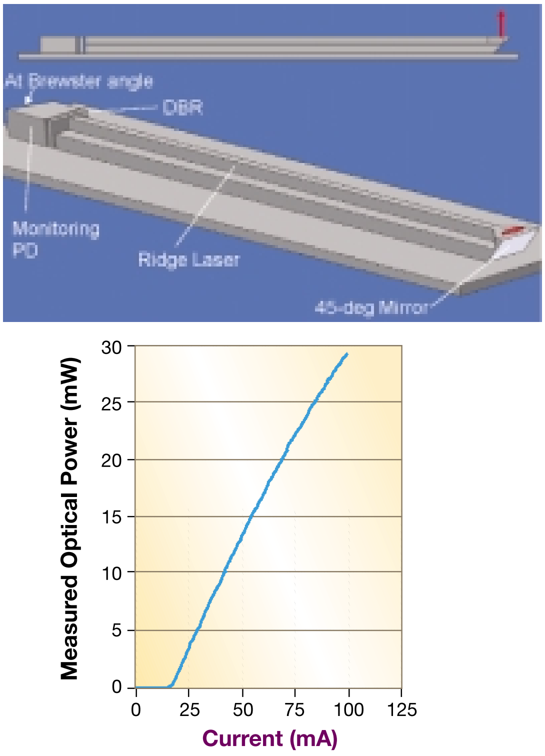

Figure 2 EFT created 45° etched facets to change a horizontal cavity laser to a surface-emitter (top). Light versus current characteristics of a HCSEL (bottom) show high output power and slope efficiency similar to those of edge-emitting lasers and higher than those achievable with single-mode VCSELs.

Horizontal Lasing

More recently, we have used the EFT process to create a new kind of surface-emitting laser. Research groups around the world have expended much effort over the last decade to develop 1310-nm and 1550-nm vertical-cavity surface-emitting lasers (VCSELs), but the realization of a reliable, high-power, long-wavelength VCSEL has been elusive. There are two primary reasons behind this difficulty: lack of high-index contrast materials compatible with InP for the VCSEL mirrors, and the fact that non-radiative processes are more significant in InP-based lasers than in GaAs-based lasers.

Surface emitters are cheaper to fabricate, test, and package than edge-emitting lasers. Building on the reliability of edge-emitting, long-wavelength lasers with etched facets, our group has developed a horizontal-cavity surface-emitting laser (HCSEL) that operates at 1310 nm.[3]

The approach had not been explored in the past because angled facets cannot be made by cleaving; this problem does not exist for EFT. The device incorporates a horizontal ridge-waveguide laser cavity with an integrated 45° etched facet at one end (see figure 2). The light generated by the device undergoes total internal reflection at this facet and is directed perpendicular to the direction of light travel in the cavity. We expanded the ridge above the 45° mirror to prevent the ridge structure from interfering with the shape of the output beam. The other end of the laser cavity includes a DBR for high reflectivity and a monitoring photodetector (MPD), the backside of which incorporates a Brewster-angle facet to eliminate back reflection.

We tested the devices to compare output to that of a VCSEL. The devices have been shown to generate more than 20 mW of optical output with slope efficiencies of 0.35 W/A. In comparison, single mode long wavelength VCSELs typically produce a maximum of about 2 mW at room temperature. At present, the HCSEL has a higher threshold current than its counterpart, but optimization will allow significant improvements in this parameter.

EFT in Action

This approach for making a high-power, high-reliability, surface-emitting laser can yield integrated chips for a number of applications. We have, for example, integrated a HCSEL with a high-speed detector to form an easily packaged bi-directional transceiver chip for passive optical networks (PONs).[4] The yield, reliability, and power output of a long-wavelength VCSEL are not adequate for PON applications at present, and the devices cannot be integrated like HCSELs.

The horizontal devices are not ideal in all respects, of course. The shape of the output beam of a HCSEL is similar to that of an edge-emitter—somewhat elliptical, but spatially well confined. VCSELs generate a larger-diameter circular output beam (9 to 24 µm in diameter compared to the 1 × 3 µm HCSEL beam). The VCSEL beam couples very effectively to multimode fiber; the beam size, however, makes efficient coupling to single-mode fiber more difficult. Hence, both types require a lens in the optical path for single-mode applications.

The semiconductor ring laser is another unique EFT-based device.[5] We can use ring lasers for high-speed digital optical switches and photonic logic gates. Our photonic logic concept uses a bi-directional ring laser as the basic building block. A closed ring cavity of this kind naturally supports two counter-propagating beams that simultaneously exit the laser at the apex in two directions. We can modify the relative intensity of the two beams in a number of ways, most easily by inserting a small reflective facet perpendicular to one of the two output beams. The ring lasers have demonstrated optical-switching speeds greater than 10 GB/s, with the potential for speeds greater than 100 GB/s in theory.

Cost-effective photonics integration has been an elusive target for many years. EFT makes possible the monolithic integration of a wide range of photonics functions using InP and other semiconductor materials. The approach allows wafer-scale processing and testing, and eliminates many of the steps commonly used in laser processing that cause low yields and defects. **oe**

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