# Chapter 8

# EPITAXIAL LIFT-OFF AND RELATED TECHNIQUES

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## 1. INTRODUCTION

Optical systems inevitably need electronic as well as optical components. A major challenge is to combine electronic and optical functions in a way that will obtain the best performance (which includes reliability) for the lowest cost. There is a spectrum of methods to try to accomplish this (Fig. 1). At one end is the purely-hybrid approach of assembling the various components with solders, wire bonds, epoxies, etc. This approach has been highly successful in achieving high performance, particularly at lower frequencies where parasitics are not a limiting factor, but it is costly because the assembly is done serially—one module at a time—and often the results depend on the

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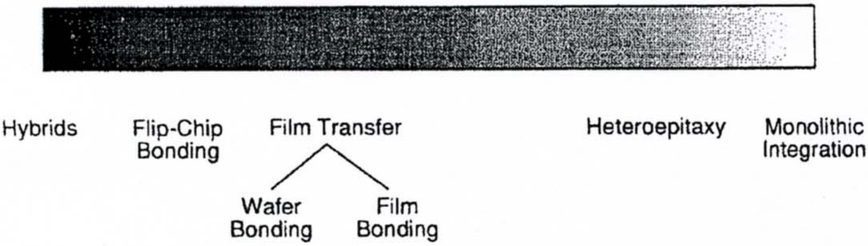


**Fig. 1.** Spectrum of the various approaches to optoelectronic integration. Monolithic integration is at one end and hybrids are at the opposite end. In the middle are different approaches that try to address the weaknesses of monolithic integration and hybrids.

skill of the assembler. At the other end of the spectrum, following the development of electronic integrated circuit technology, considerable effort has been expended in the monolithic integration of electronic and optical devices. The strength of this approach is that many circuits are made in parallel, in a highly reproducible manner, and with greatly reduced electrical parasitics by employing thin-film fabrication techniques commonly used in making integrated circuits. However, a drawback of monolithic integration is that one is forced to realize all the functions in a semiconductor material system that is dictated primarily by the wavelength of light to be used. Not every device made with the chosen material system would be the best possible for the application, and consequently the overall performance of the integrated circuit may be worse than that of the corresponding hybrid where one has the freedom to choose the best type of device for each function. Between these two extremes are various methods that address these fundamental problems. One of the goals of heteroepitaxy, such as the growth of GaAs on Si, is to enable the monolithic integration of GaAs optical devices with Si electronics so one can have the best of both technologies on a single substrate. In spite of the advances made in this area over the last decade, there remain serious questions on material quality and there are many material combinations of technological interest, such as InP on $LiNbO_3$, that cannot be realized with the current state of the art.

Closer to the hybrid end of the spectrum are several related methods referred to here collectively as film transfer. They have the common theme of bonding a thin device film to a host substrate to avoid growing the film directly on the host, but they differ in the details of how this is accomplished. The film is often less than a few micrometers thick, in some cases comprising only the necessary device layers, and is attached with at most a thin layer of solder or adhesive. The result is a structure that is sufficiently planar for thin-film fabrication techniques to delineate small features with accurate alignment and low electrical parasitics. The two essential steps of film transfer are separating the film from its growth substrate and bonding it to the host. If the film is separated before it is bonded, we have the film bonding techniques; but if the film is bonded before it is separated, we have the wafer bonding techniques. Device fabrication may occur before (preprocessing) or after (postprocessing) the transfer, resulting in four strategies that we will be discussing.

A final entry in the spectrum is flip-chip bonding [1], also known as solder bonding or C-4 (controlled collapse chip connection) processing. A completed chip is bonded to a substrate by small balls of solder, which usually double as electrical interconnects. The boundary between film transfer and flip-chip bonding is not sharp. Flip-chip bonding may be thought of as wafer bonding of preprocessed devices, with the bonds made only at selected areas. But with all of the interconnects made as an integral part of bonding, further processing is often unnecessary and the film separation step is superfluous.

## 2. TECHNIQUE

In this section, we will review film transfer techniques relevant to optoelectronics. We will then concentrate on epitaxial lift-off (ELO) because it is the most widely used method for optoelectronics. Rather than compare in detail variations that have evolved in different laboratories working on ELO, we will try give an overview and point out major variations.

### 2.1. Film Transfer Techniques

An early publication by Konagai *et al.* [2] on film bonding was the peeled film technology (PFT), in which a film was separated from its growth substrate by a highly selective etch of a sacrificial layer with hydrofluoric acid and attached to a host substrate in an unspecified way. This was based on a proposal by Milnes and Feucht [3]. Konagai *et al.* also proposed stacking many device and sacrificial layers to obtain many transferable films with a single growth. In ELO, which will described in greater detail in the following section, the device film also is separated (lifted off) from its growth substrate by highly selective chemical etches and then attached (grafted) to the host substrate by van der Waals forces [4, 5]. In another film bonding technique, cleavage of lateral epitaxial films for transfer (CLEFT) [6], the film is separated from the growth substrate by cleaving along the interface (parallel to the growth surface), which was weakened by narrow carbon stripes deposited before the start of growth. In film bonding, there is a point in which the fragile film is supported by neither the growth nor the host substrate. Film handling at this critical point is facilitated by a relatively thick wax or polymer film in PFT and ELO or by wafer bonding to a temporary substrate in CLEFT.

In the wafer bonding methods, wafers are bonded together before the device film is separated, bypassing the need to handle thin films. The device layer finishes in an upside-down position in the wafer bonding techniques. The first effort was by Stern and Woodall [7], who separated bonded GaAs laser diodes from their growth substrate by using hydrochloric acid to etch an aluminum-rich AlGaAs sacrificial layer. Now, the most widely used wafer bonding technique, known as direct bonding or bond-and-etchback silicon on insulator (BESOI), is the bonding of the thermal oxides on silicon wafers to obtain silicon-on-insulator (SOI) wafers [8–10]. The oxide layers of the mating wafers are fused together at temperatures as high as 1400°C, resulting in an interface as strong as fused quartz; lower temperatures can still yield strong bonds. One wafer is thinned either by mechanical lapping or chemical etching to a thickness suitable for device fabrication. This process has been adapted so that one of the wafers can be InP or GaAs [11, 12]. Low-temperature glass [13], metal [14, 15], and organic adhesive [16] have also been used to bond a growth wafer to a host substrate. Anodic or field-assisted bonding of GaAs to glass has been reported as well [17]. Two semiconductor wafers heated while in direct contact can fuse together by forming an alloy at the interface [18]. InP and GaAs wafers have been fused together with variations of this technique [19, 20].

## 2.2. Epitaxial Lift-off

The method used to remove the epitaxial films from their growth substrates depends on the material system. In the GaAs-AlAs system, a sacrificial layer of AlAs is undercut to separate the epitaxial film from the GaAs growth substrate. This method exploits the high selectivity of hydrofluoric acid in etching AlAs without etching GaAs. In the InP-$In_{0.53}Ga_{0.47}As$ system, the InP substrate selectively etches in hydrochloric acid with a layer of $In_{0.53}Ga_{0.47}As$ as an etch stop. Although a sacrificial layer of $In_{0.53}Ga_{0.47}As$ sandwiched between the InP substrate and an InP layer or a 5-nm-thick pseudomorphic AlAs layer could be used with a phosphoric acid–peroxide–water or hydrofluoric acid etch, respectively, it is more convenient to remove the substrate.

The most commonly employed ELO procedure begins by covering the top of the wafer with Apiezon W wax, making sure that no wax has run over the edge. If the device structure includes layers that will be attacked by the selective etch, they can be protected by etching the periphery of the wafer past these layers and covering the side walls with wax, or by etching mesas past these layers in the case of preprocessed devices. Next, the coated wafer is immersed in HF for GaAs or HCl for InP. Typical times are overnight for a centimeter-square GaAs sample and an hour for an InP sample of any size. Because of the high selectivity of these etches, the samples can be overetched considerably without any ill effects. When the film has separated from the substrate, it is rinsed in deionized water and transferred to the new substrate. It is important that the host substrate be flat for the film to adhere. When grafting to a silicon wafer on which circuits have been made, it is necessary to planarize the wafer first [21, 22]. In the basic ELO process, the film is free to slide on a thin layer of deionized water that was dragged out with it. When the film is correctly positioned, the water is gently squeezed out and the assembly is allowed to dry, often with a weight or spring load on top. As the water dries, surface tension from the water film pulls the film and the substrate closer together until short-range, attractive van der Waals forces hold them together. The wax can then be removed.

Cross-sectional transmission electron microscopy studies show there is an amorphous interfacial layer whose thickness can vary from zero to only a few tens of nanometers along the interface [5]. The composition of this layer probably includes the hydrated oxides of the film and its host.

## 2.3. Device Fabrication

There are two strategies for making devices on the transferred film. One is to preprocess the devices and transfer completed devices; the other is to postprocess the devices on a bare grafted film. Some processing, such as the deposition of an adhesion, contact, or passivation layer, may be done to the underside of the film in either case. The important distinction between pre- and postprocessing is that the film must be accurately aligned for bonding in preprocessing but need not be in postprocessing. Postprocessing is the only option in some wafer bonding methods because of the high temperatures needed for the bonding processes; moreover, in some cases, the preprocessed devices are upside-down after bonding and may require additional etch steps to be contacted from above.

Film transfer with preprocessed devices becomes very much like a hybrid technology, but with much thinner layers to enable thin-film technology to be used for low parasitic and high-density interconnects. Advantages of preprocessing over postprocessing are that one can use standard devices, perhaps from a foundry, that the processing of the grafted devices and the processing of the host devices do not interfere with each other, that one can graft devices tested to be good, and that little of the film is wasted if diced chips are grafted one at a time. Completed devices are thus lifted off and grafted to the new substrate, perhaps with devices already on it, and interconnected using one or more levels of metallization and interlevel dielectric. Because it is desirable to dice the film into chips and graft each chip independently, chip separation techniques compatible with ELO have been investigated [23, 24]. Without going to a direct-write lithography system that can be custom programmed for each grafted chip, the alignment of devices on the grafted film with those on the host substrate is of utmost importance. One may have large pads to ensure that interconnections can be made with a fixed mask in the presence of some misalignment error, but the penalty in excess capacitance or real estate consumption may offset any potential advantages of film transfer. Accurate placement of ELO chips is therefore currently being investigated: The lifted-off chips are temporarily grafted to a transparent polyimide film and their alignment to the host is done with a contact mask aligner to obtain 2-μm alignment accuracy [24]. Manipulators with motorized micrometers can give a few micrometers accuracy [23]. An ELO film has also been self-aligned to the substrate with 5-μm accuracy with the surface tension of water by pretreating the substrate so that it is hydrophilic in the region where the film is to attach and hydrophobic elsewhere [25].

Another concern is that stresses from materials deposited in making the preprocessed device may bow the ELO film to such an extent that it interferes with the film transfer [26]. Although low stress metallization and dielectric layers as well as stress-compensating layers can reduce the bowing, these may not always be practical. Moreover, stress can be present even in bare, unprocessed films because of slight changes in the lattice parameter through the film. For example, AlAs, often taken to be perfectly lattice matched to GaAs, is actually about 0.1% mismatched, so any asymmetric GaAs-AlGaAs heterostructure has an intrinsic stress.

The other approach is to postprocess the film, i.e., totally fabricate the devices on a bare grafted film. This obviously eliminates the need for precision alignment when bonding the film and has the added advantages that one may be able to compensate for changes arising from the different environment of the film (such as back surface depletion of a field-effect transistor) during the device fabrication and that one can intermix the processing steps of the host and ELO film devices to obtain a richer set of structures than by grafting preprocessed devices. As mentioned, postprocessing may be the only option for some of the wafer bonding methods. Although submicrometer device alignment is readily achieved with postprocessing, one faces the problems associated with device fabrication on grafted films, including film adhesion and elevated-temperature (>300°C) processing.

The succession of processing steps typical of optoelectronic device fabrication places a more stringent demand on film adhesion than that from the one or two steps required to interconnect preprocessed devices. In some applications, moreover, it is essential to remove all semiconductor between device mesas. With pure van der Waals bonded films, many mesas do not adhere once they are isolated [27]. The adhesion is enhanced by substituting the van der Waals bonds between the ELO film and substrate with a stronger bond. A thin layer of palladium [28] or indium [29] has been used to join the film to the host while making an $n$-type ohmic contact to the bottom of the film. Palladium bonding is particularly attractive because it occurs at room temperature. Gold [30] or a gold–zinc [24] alloy can likewise make a $p$-type contact to the bottom of the film. Organic glues and adhesives can be used but they need to be chosen carefully because, during cure, many of them shrink and release a reaction product, such as water, that can be trapped under the film. Also, most of them cannot tolerate high temperatures. Grafting to a thin, cured polyimide layer improves adhesion, particularly when the host is not flat [31]. Another method that has successfully enhanced adhesion of mesas is to "tape" them down by straddling the mesa with a material that adheres well both to it and to the substrate before completely separating the mesas [32].

The dominant effect of high-temperature processing is the formation of blisters and craters up to 0.5 mm in diameter that result from the vaporization of entrapped material, such as small particles or water [33, 34]. The density of trapped particles decreases when the processing is done in a clean-room environment. Most particles are introduced during transfer of the film from the etch solution to the rinse and from the rinse to the host substrate. An all-underwater process in which the etch solution is replaced by rinse water and all film handling is done completely within the rinse water greatly reduces the particle density [23]. A vacuum prebake is sometimes beneficial in removing trapped water, but a more practical solution is to etch the film into mesas before any high-temperature processing [35]. This uncovers the trapped material in area between mesas, limits any blistering to one mesa rather than to an extended area, and provides a short escape path (tens of micrometers) for vapors both during the high-temperature process itself and during a vacuum prebake.

## 3. APPLICATIONS

The types of applications reported for ELO and film transfer in general fall into three broad, although not mutually exclusive, categories. First are those in which ELO is a form of hybrid technology, and grafted devices are electrically interconnected with devices on the host substrate. Second are those in which some detrimental property of the growth substrate is eliminated by separating the growth substrate from the device layers and replacing the substrate with one that is more suitable. Finally, there are those in which the grafted film interacts with the host substrate or a device on the host substrate in a manner that cannot be mediated by an interconnect wire.

### 3.1. Interconnecting Devices

Much of the effort in using ELO as a hybrid technology has concentrated on grafting III–V optical devices to a silicon wafer where there can be complex electronics. Typical applications envisaged are optical interconnects between chips, displays with complex driver circuits, and signal processing by silicon electronics in an optical communication system. Lasers [15, 36], light-emitting diodes (LEDs) [24, 37], and optical modulators [30, 38, 39] have all been grafted to bare silicon. Making ELO lasers with cleaved facets introduced some complications to the fabrication [36]. Photodetectors [21] and LEDs [22] have been grafted to and interconnected with working circuits on a silicon wafer. Another active area is the grafting of GaAs electronics onto a new host substrate. GaAs metal–semiconductor field-effect transistors (MESFETs) [40], high-electron-mobility transistors (HEMTs) [41], and resonant tunneling diodes [29] have been grafted to glass as a demonstration of the ELO technique. III–V devices have been grafted to III–V hosts to combine GaAs MESFETs with long-wavelength optical devices [25, 42]. GaAs MESFETs have been grafted to an $LiNbO_3$ modulator to provide on-wafer drive electronics [43]. III–V electronic devices can operate at very high speeds, but their integrated circuit technology lags that of silicon. The integration of silicon VLSI electronics with high-speed III–V electronics in critical areas is an attractive alternative for obtaining both high speed and high complexity. With this as a motivation, both GaAs MESFETs and HEMTs grafted on silicon have been reported [44, 45]. ELO offers an advantage over heteroepitaxy in that the material of the layer between the silicon and GaAs devices need not be GaAs but can be chosen to minimize the parasitic capacitances that degrade the speed of the GaAs circuit [35].

### 3.2. Altering Substrate Properties

The growth substrate does not always have the best properties for device performance. For example, the dielectric constant of a GaAs or InP substrate is high, leading to high interconnect and bond pad capacitances that may degrade the speed. Grafting a high-speed device to a substrate with lower dielectric constant, such as beryllia or sapphire, reduces these parasitic capacitances [46, 47]. Similarly, grafting a laser to a substrate with a lower index of refraction alters its spontaneous emission spectrum [48]. ELO has also been used to avoid the traps present in semi-insulating GaAs substrates that lead to sidegating and leakage currents [35]. Optical absorption of the substrate can been avoided by ELO [49, 50]. The issue of high substrate cost for solar cells was addressed by lifting off the solar cells from the growth substrate and reusing the growth substrate [2].

There are times when the available growth substrates are not adequate even for growth. The alloy system InGaAsP spans a two-dimensional compositional space, but only the compositions lattice matched to a binary are routinely accessible. ELO can create new substrates with lattice constants different from those of the binaries. When a strained layer below its critical thickness is lifted off and grafted to a host, its lattice parameter relaxes to a value previously unavailable for growth [51]. A variation of this idea is to relieve the stress in a strained layer grown on a sacrificial layer [52–54]. The sacrificial layer underneath etched mesas is partially undercut-etched to form stress-relieved cantilevers that are kept in place by the unetched portion of the sacrificial layer.

ELO can also be an aid for analysis of optoelectronic materials. Without the substrate, a secondary ion mass spectrometry (SIMS) analysis can begin from the back of a layer to obtain better depth resolution there and to avoid possible interference from material near the top surface [55, 56].

### 3.3. Merging Devices

The third class of applications merges grafted devices with either the host substrate or devices on the host substrate so that they interact in ways other than through a metal wire. ELO presents an opportunity to do this because the glueless bonding of films consisting of only the necessary layers allows the active region of the film and substrate to be separated vertically by only a few tens of nanometers. Interactions with short characteristic lengths become a possibility. An analogy in electronics would better illustrate the point: Although a bipolar transistor consists of two $p$–$n$ junction diodes, it is not possible to make a hybrid bipolar transistor from two discrete diodes because it is necessary that the diodes be less than a few minority-carrier diffusion lengths apart.

A simple form of optical interaction mediated by ELO is a waveguide formed with a grafted guiding layer and host substrate cladding layer [57]. Semiconductor quarter-wave stacks have been grafted to fibers to form optical resonators [58]. Grafted semiconductor films have also been vertically coupled to optical waveguides of ion-exchanged glass and proton-exchanged $LiNbO_3$ [59–61] for waveguide detectors. Enhanced optical coupling that is insensitive to the details of the bonded interface has been achieved by burying the semiconductor layer in the core of the waveguide for detector [62] and emitter [63]. A laser was grafted at the bottom of a well to butt-couple it to a glass waveguide [14]. A high-reflectivity bottom mirror that is insensitive to the wavelength and the incidence angle of light has been obtained by grafting a film to metal and used to reduce the threshold current of lasers [7] or to enhance the quantum efficiency of LEDs [64, 65] by recycling photons that would otherwise be lost in the substrate.

Grafting a GaAs film on a narrow metal finger results in a Schottky diode between them that can apply an electric field in the semiconductor to collect photogenerated carriers for an inverted metal–semiconductor–metal (MSM) photodetector [66] or to deplete and undeplete the GaAs for an inverted gate MESFET [67]. When a film is grafted to a substrate with ribs on its surface, the film bends as it tries to conform to the rib. The bending stress can alter the semiconductor band structure substantially in the vicinity of a rib, as demonstrated by the redshift of the exciton peak from an expediently placed quantum well in the grafted film [68]. Applying an electrostatic potential between the film and substrate modulates the amount of redshift [69].

## 4. UNANSWERED QUESTIONS

In spite of its successes, ELO is still at an early stage of development and many important questions have not been answered. Included are questions concerning the reliability of grafted devices and the chemical and physical nature of the grafted film and the bonded interface. These questions apply not just to ELO but to all film transfer techniques.

In addition to the usual reliability concerns about semiconductor devices, several issues are unique to ELO. First is trapped dust particles and how they affect yield. Second is the film adhesion as influenced by mechanical, thermal, and electrical stresses. Encapsulating the film is one way to prevent adhesion failure. However, devices will almost certainly be grafted to host substrates of different materials, so the effects of differential thermal expansion need to be studied. Under some conditions, there is slippage at the van der Waals bonded interface even during modest thermal cycling [70]. The effect of differential thermal expansion can be minimized by doing the bonding at a different temperature, such as the middle of the intended operating temperature range. Another concern is the bottom, exposed surface that is very close to the active layers. Top and bottom capping layers of either epitaxial semiconductor or separately deposited dielectric to protect the active layers would help, but these may interfere with device function and certainly would add to the step height that interconnects would have to cover. Again, an encapsulant should be beneficial. Another question is whether inhomogeneities in the bonding can cause local peaks in the stress or in the temperature rise and thereby accelerate failure. In the case of bonding with some sort of thick adhesive, stresses arising from the bonding process or from differential thermal expansion need to be investigated.

Many types of optical and electronic compound semiconductors have been made by ELO and related film transfer techniques. Performance comparisons that have been made against devices fabricated on the growth wafer are very favorable, quite often with differences within the normal variations seen among devices that are nominally the same. However, more stringent comparisons are required in some cases: lasers made by ELO have been broad-area lasers that are not too sensitive to material quality, and the only reported transferred film, single transverse mode lasers were made by wafer bonding rather than film bonding [14, 15]. Small changes in the dark current of InGaAs p-i-n photodetectors [61], but not of GaAs MSM photodetectors [21], have been reported; a more systematic study is required in this area. Except for one continuous test of an ELO MESFET that showed no change after 100 hours at room temperature [45], device degradation has not been studied.

A better understanding of the van der Waals bonding process and the resultant interface is required. The bonded interface can affect the device reliability, the $1/f$ noise properties, and the performance of merged devices, where some interaction takes place through the interface. With a fundamental understanding of the interface, it may even be possible to engineer it to the specific needs of the device. We also need to see if there are subtle changes in the ELO film that may be apparent only with more stringent testing.

Many possible ELO applications involve devices, such as lasers and power transistors, that have large power dissipation. Even assuming that the interfacial layer has the thermal conductivity of the worst solid conductor, the thermal resistance is extremely small because of the thinness of the layer. Although the ELO bond itself does not limit the heat dissipation, the host substrate in some instances would necessarily be a poor thermal conductor. Heat dissipation will probably be a limitation in such applications as driver electronics or lasers grafted on poor thermal conductors such as $LiNbO_3$ or glass. The heat can be removed by some other channel in such cases, but the overall complexity in the final packaged device may negate any advantages gain by ELO.

## 5. OUTLOOK

Assuming that all concerns about reliability and material quality prove to be unfounded or are adequately addressed, what is the outlook for ELO and other film transfer techniques? An assessment requires comparison with other methods capable of achieving similar performance in a particular application. For electrically interconnecting dissimilar devices with low parasitics, flip-chip bonding, already a well-established technique, is an alternative. High speeds (>20 GHz) have been demonstrated for flip-chip bonded detectors [71], and infrared focal plane arrays with more than 65,000 connections between the detector array and the silicon circuit have been made with 30-μm-square pixels [72]. A potential advantage of film transfer techniques is that of attaining even higher densities of interconnects. Optics and electronics are less densely interconnected to each other for most other optoelectronic applications than they are in focal plane arrays, so film transfer techniques do not offer any obvious advantages over flip-chip bonding here. Purely electronic applications will very likely require a high interconnect density between grafted and host substrate devices, so this may be an important area for film transfer. Another difference between film bonding and flip-chip bonding is in the orientation of the device; in applications where the device cannot be bonded upside-down, ELO and film bonding is certainly the more attractive option.

Success of film transfer for electrical interconnect applications, therefore, relies on finding applications in which flip-chip bonding either cannot provide adequate interconnect density or gives the wrong device orientation. In the other classes of applications just described, altering substrate properties and merging devices, no well-established competing method exists for accomplishing these goals and film transfer can become an important technology.

Heteroepitaxy, which is also in an early stage of development, is an alternative to film transfer for some of the applications considered. Film transfer, at this time, offers better material quality and a far larger variety of material combinations than heteroepitaxy does. Even compared to the most advanced heteroepitaxial system, GaAs on Si, film transfer offers more flexibility through lower processing temperatures and through the wider choice of buffer layers between the Si and GaAs.

Film transfer is manufacturable; silicon bipolar circuits made on direct bonded SOI wafers are commercially available [73]. But for the optoelectronics and compound semiconductors, it is not clear at this point exactly which variation of film transfer will be the most suitable for various purposes. The intended application will control the choices in many cases, so there may be different methods for different applications.

## 6. CONCLUSION

Film transfer techniques for optoelectronics in the last few years went to a stage of favorable initial demonstrations. Workers from laboratories around the world made grafted optoelectronic devices and were encouraged by the similarity of the performance of grafted devices to that of conventionally made devices. The time has already come to examine the performance of grafted devices critically in terms of reliability, performance, and uniformity and to consider where these techniques will have an impact in optoelectronics. In the next few years, we expect more commercial penetration of film transfer techniques to solve manufacturing, packaging, and systems problems.

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