Transfer Printing of Microscale Compound Semiconductor Devices

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Abstract

Heterogeneous integration of microscale compound semiconductors with silicon or other substrates offers a cost competitive path to the commercialization of such devices. Micro-transfer printing is a well characterized micro-assembly technique that has been demonstrated for several compound semiconductor applications. In this paper, we describe practical methodologies for heterogeneous integration of compound semiconductors with non-native substrates. We also present examples of common III-V devices, integrated with non-native substrates.

INTRODUCTION

Compound semiconductors are the preferred materials for many semiconductor and optoelectronic devices. However, in many cases, these materials find it difficult to compete with silicon technology in terms of cost and scalability. As more applications are developed with III-V materials, there is a growing need for scalable and cost effective ways to integrate these devices with silicon, glass, polymer, ceramic or other substrates that are more cost effective or provide unique performance benefits. One of the methods of performing such heterogeneous integration is transfer printing using engineered elastomer stamps. Transfer printing is a scalable, massively parallel and high throughput method for micro-assembly that has been demonstrated at a pilot scale for several years.

MICRO TRANSFER PRINTING METHODOLOGY

Micro transfer printing (μTP) was originally conceived in Professor John Rogers' laboratory at the University of Illinois over ten years ago [1, 2] and has been under continuous development since its creation [3 - 5]. It involves the release and transfer of device arrays from their growth substrate to non-native target substrates in a massively parallel manner (i.e. thousands of devices per transfer) with a high degree of positional accuracy. A key element in transferring the devices is an elastomer stamp that removes the devices from the growth substrate using rate-dependent viscoelastic adhesion [2] and "prints" them to a desired receiving surface. The stamps are fabricated by injection molding of the elastomer against a reusable master wafer, where relief on the master wafer generates thousands of elastomer posts on the surface of the stamp. Figure 1 presents a schematic depiction of a transfer stamp after picking devices from a source wafer. The stamps are naturally compliant in the z-dimension, enabling them to be in contact with the source surface even if the surface is not perfectly flat. Figure 2(a) is a simple cartoon cross section of a transfer stamp, and illustrates how the stamp is compliant in the vertical dimension, while remaining stiff in the lateral dimensions. The lateral stiffness of the stamp allows the parallel transfer of thousands of devices, while maintaining the fidelity of the device array. The soft nature of the elastomer facilitates damage free transfer of thin and fragile micro devices.

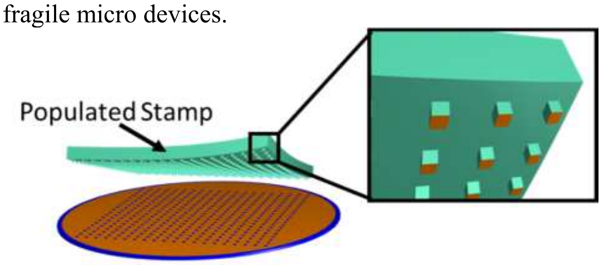

Figure 1: Schematic depiction of a stamp removing devices from a source wafer. The inset illustrates that individual posts are populated with a single device per post.

The stamp integrates into simple, highly-scalable motion-plus-optics automated machinery. Figure 2(b) is an image of the print head. The machine optics move independently of the print head and are used for alignment, looking through the transparent stamp. Existing tools perform printing onto small to large wafer formats and panels up to 400 mm x 500 mm. Figure 2(c) is a photograph of a printer designed to populate 400 mm x 500 mm panels that resides at the Tyndall National Institute in Cork, Ireland. Printer development has gone through several design and prototype stages since 2006.

A typical process flow for integrating a compound semiconductor device onto a non-native substrate is presented in Figure 3. The source wafer is prepared by growing a suitable sacrificial layer on the substrate and then depositing the required epitaxial stack by MOCVD or MBE,

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as shown in Figure 3(a). The release layer must be capable of being selectively etched without impacting the device layers and must be compatible with the crystal structure of the device layers that are grown. The device is fabricated using standard semiconductor processes after epitaxial growth is complete. Figure 3(b) presents a generic structure with etched mesas and metal contacts. In this process, the perimeter of the device is etched down to the sacrificial layer. The device is then encapsulated with a polymer, which protects the device during transfer and also serves to anchor the device to the substrate. The anchor keeps the device attached to the substrate during the release process. The final step in preparing the source wafer for printing is the selective etching of the sacrificial layers. These steps are depicted in Figure 3(c). Figure 3(d) illustrates a stamp removing a device from the native growth substrate. The elastomer post adheres to the device by Van der Waals forces and the stamp is raised up, fracturing the polymer tether at a designated location. The stamp is now populated with an array of devices. Finally, the populated stamp is moved to the non-native destination substrate, aligned and the devices transferred, as presented in Figure 3(e). The polymer encapsulation is removed after the devices are transferred onto the receiving substrate.

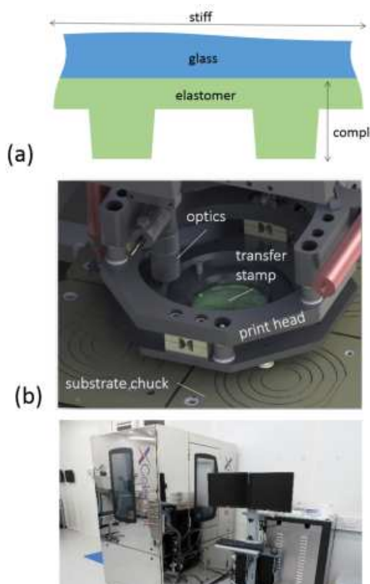

Figure 2: (a) cross-section illustration of a transfer stamp and (b) an image showing how the stamp is integrated into the print head and (c) a photograph of the print tool at Tyndall National Institute in Cork, Ireland.

Figure 4 illustrates some common bond interfaces employed in transfer printing. Direct bonding is effective when the bottom surface of the device and the receiving surface of the non-native substrate are smooth. The strength of direct bond interfaces can optionally be enhanced through ex-situ annealing. Direct bond interfaces are a good approach in applications that require low thermal resistance to the substrate [6]. Examples of Gallium Arsenide and Indium Phosphide direct bonded to Silicon are shown in Figure 5(a-c).

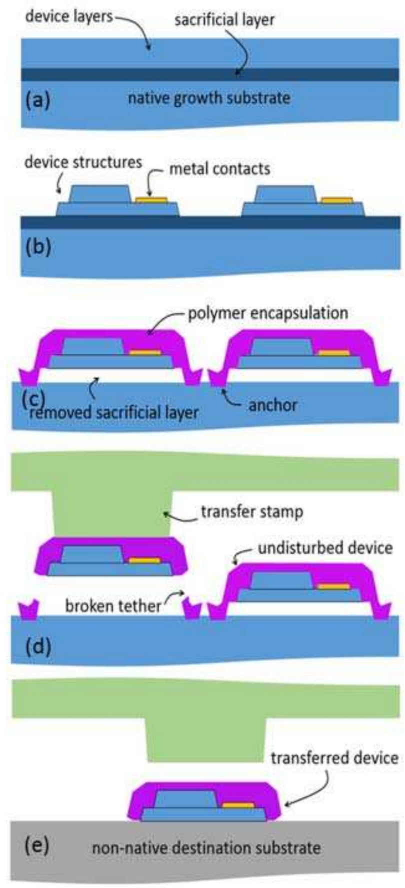

Figure 3: Common process flow for heterogeneous integration of compound semiconductors to non-native substrates (adapted from [5]).

In applications that do not demand low thermal resistance, it is common to employ semiconductor-grade resins on the destination substrate before printing. These resins such as polyimides, BCB or epoxies are effective at planarizing rough, or intentionally patterned surfaces, as illustrated in Figure 4. The uncured resins maintain some compliance and enable very high print yields (> 99.9%) [7]. An *ex-situ* bake is used to fully cure the resin after printing. Examples of compound semiconductor devices printed to planarizing resin are shown in Figure 5 (d-f).

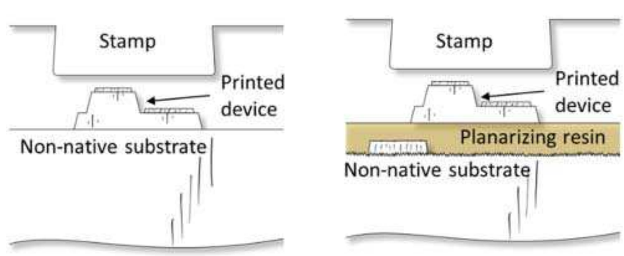

Figure 4: Schematic illustration of two common types of bonding interfaces employed in transfer printing.

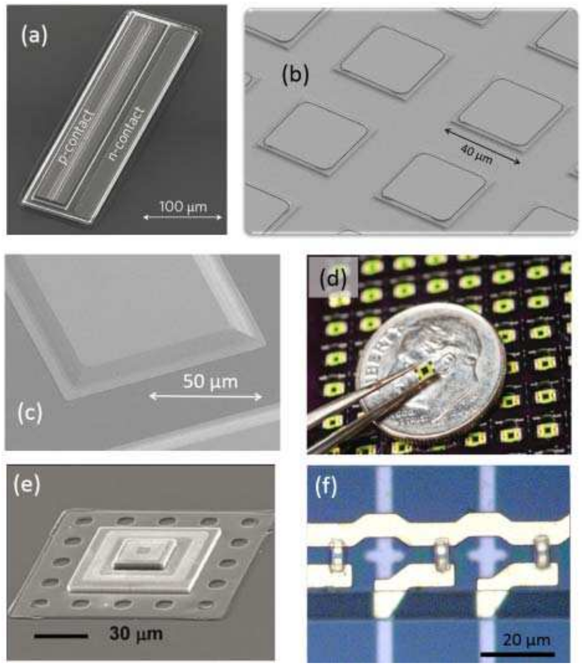

Figure 5: Examples of printed compound semiconductors with direct bond interfaces: (a) etched facet Gallium Arsenide laser on Silicon (adapted from [6]), (b) Gallium Arsenide devices (40 x 40 x 1 um) printed to silicon [5], and (c) a coupon of Indium Phosphide printed to Silicon [5]. Examples of printed compound semiconductors with planarizing resin bond interfaces: (d) multi-junction Gallium Arsenide based solar cells printed onto ceramic (adapted from [8]), (e) Gallium Arsenide vertical cavity surface emitting laser printed onto plastic (adapted from [9]) and (f) microscale Gallium Arsenide and Gallium Nitride light emitting diodes printed onto glass [10].

ATTRIBUTES OF MICRO TRANSFER PRINTING

µTP is a powerful micro-assembly technology with many advantages over conventional approaches. µTP is ideal for handling devices that are too small, too fragile or too numerous to handle by any other means. For example, devices as small as $3x10\,\mu^2$ µ-ILEDs and as numerous as 10,800 have been printed in one print cycle for a display application [10]. The use of µTP allows for the decoupling of epitaxial growth from the application of the device. High quality epitaxial growth requires a lattice matched substrate such as GaAs or InP that may be subjected to high temperatures, whereas the ideal application substrate may be a non-native substrate such as glass, silicon, ceramic or flexible polymer. µTP also allows substrates of different sizes to be used efficiently. For example, devices from a 150 mm GaAs substrate can be transferred to a 200 mm silicon wafer efficiently using µTP, which may be more challenging in conventional wafer bonding.

µTP allows for efficient usage of the relatively expensive III-V devices by allowing them to be fabricated densely on the native substrate, while using them sparsely and more cost effectively on the receiving substrate. This multiplicative effect allows designs where one compound semiconductor source wafer to populate several target wafers. In addition, etched streets are typically smaller than dicing streets, allowing more III-V material to be used to make devices. µTP also enables re-use of the growth substrate after the active devices have been removed from the substrate and the substrate cleaned.

µTP is massively parallel. Arrays of thousands of devices can be transferred in a single print operation. This attribute, along with the ability to achieve print yield >99.9% and placement accuracies better than ±1.5 µm (3σ) makes µTP very attractive for high volume micro-assembly applications. The print operation, which involves optics and motion stages, can be performed by automated wafer level tools.

APPLICATION EXAMPLES

Microscale devices based on Gallium Arsenide, Indium Phosphide and Gallium Nitride are excellent candidates for heterogeneous integration onto silicon, glass, flexible polymers or other substrates. Several applications of interest to the compound semiconductor community have been demonstrated.

An early commercial application of µTP was in concentrated photovoltaics [8, 11], where the ability to use small, high-performance, multi-junction photovoltaic cells provides many advantages. In this application, 600 x 600 µm solar cells are printed onto low-cost ceramic substrates, and processed at wafer-level into surface mountable packages, as presented in Figure 5(d). This process has been scaled to pilot production and thousands of ceramic wafers have been printed to date with photovoltaic module efficiencies exceeding 35%. New research is focused on increasing the efficiency of multi-junction solar cells by capturing more of the solar spectrum, and µTP has been used to demonstrate mechanically stacked four junction micro solar cells [12].

Solid-state lighting and information displays are promising applications for microscale light emitting diodes (LEDs). Figure 6(a) shows an early demonstration of a display using micro transfer printed 50 x 50 µm LEDs [13]. The display is mostly transparent and is also bi-directional. Figure 6(b) is a photograph of an assembly of microscale blue (InGaN) LEDs micro transfer printed onto plastic [14]. Arrays of high performance InGaN LEDs are expected to find utility in novel lighting applications, as well as display applications. Figure 6(c) is a photograph of a 14” x 14” glass panel populated with microscale Silicon integrated circuits. This work aimed to develop large-format electronic backplanes that utilized printed microscale CMOS chips. Figure 6(d) is a photograph of a functioning active matrix display that is controlled by printed microscale CMOS chips [15]. Following these same methodologies, compound semiconductor devices can be integrated onto large-format glass or plastic substrates. In addition, these efforts illustrate that it is practical to consider the integration of microscale Silicon integrated circuits onto III-V devices, or the co-integration of both III-V and Silicon devices onto large-format glass or plastic substrates.

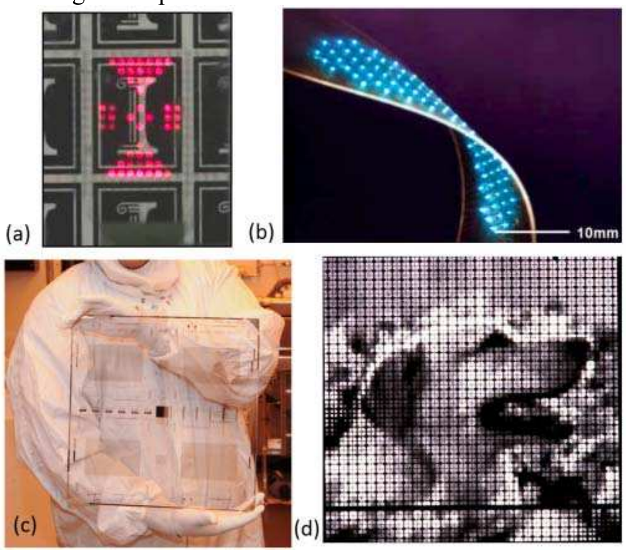

Figure 6: Examples of micro transfer printing applications include; (a) transparent and bi-directional displays using microscale LEDs (adapted from [13]), (b) flexible arrays of microscale LEDs for lighting or display applications (adapted from [14]), (c) microscale Silicon integrated circuits printed onto large format glass and (d) an image of an active matrix OLED display using transfer printed integrated circuits (adapted from [15]).

Transfer printed lasers have utility in many applications, with two examples being Silicon photonic integrated circuits (PICs) and heat-assisted magnetic recording (HAMR). Transfer printed etched-facet Gallium Arsenide lasers have been demonstrated and are a candidate for application into HAMR write heads [3, 6]. Gallium Arsenide vertical cavity surface emitting lasers (VCSELs) have been printed onto plastic substrates [3, 9] and are expected to have a wide range of applications. Print compatible devices grown on Indium Phosphide are anticipated to be useful for data communications and telecommunications. The European Commission is funding a new program called TOPHIT (Transfer print OPerations for Heterogeneous InTegration), where a consortium of companies is developing Silicon photonic integrated circuits with transfer-printed III-V components [16].

CONCLUSIONS

Micro transfer printing is an emerging technology that facilitates heterogeneous integration of microscale compound semiconductor devices onto non-native substrates. Print compatible micro-devices are fabricated on their native wafers through modified epitaxial lift-off techniques, where microstructures are designed to anchor the devices after they are undercut. Engineered viscoelastic elastomer stamps are used to accurately transfer arrays of micro devices onto useful non-native substrates in a deterministic and massively parallel manner. Many compound semiconductor devices, including multi-junction solar cells, LEDs and lasers, are well-suited for micro transfer printing, and these printed high performance devices are expected to find application in fields ranging from photovoltaics to photonic integrated circuits.

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ACRONYMS

μ-ILED: Micro inorganic light emitting diode

μTP: Micro transfer printing