Heterogeneous Integration of Microscale Semiconductor Devices By Micro-Transfer-Printing

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The 65th Electronic Components and Technology Conference

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Agenda

- Introduction
- Micro-Transfer-Printing Fundamentals
- Making Printable Devices
- Application Examples
- Conclusions & Acknowledgements

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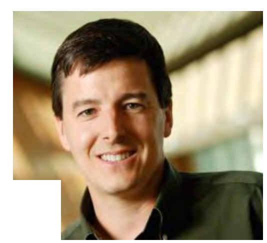
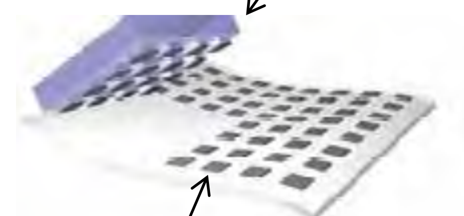
X-Celeprint introduction

RTI INTERNATIONAL

Tyndall National Institute

- Developing advanced micro assembly technology
- Headquartered in Cork, Ireland
- Subsidiary located in Research Triangle Park, North Carolina
- Founded by Professor John Rogers with core IP licensed from the University of Illinois





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ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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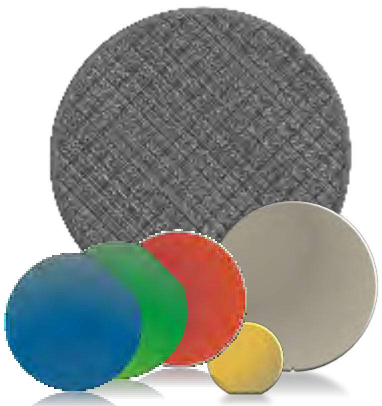
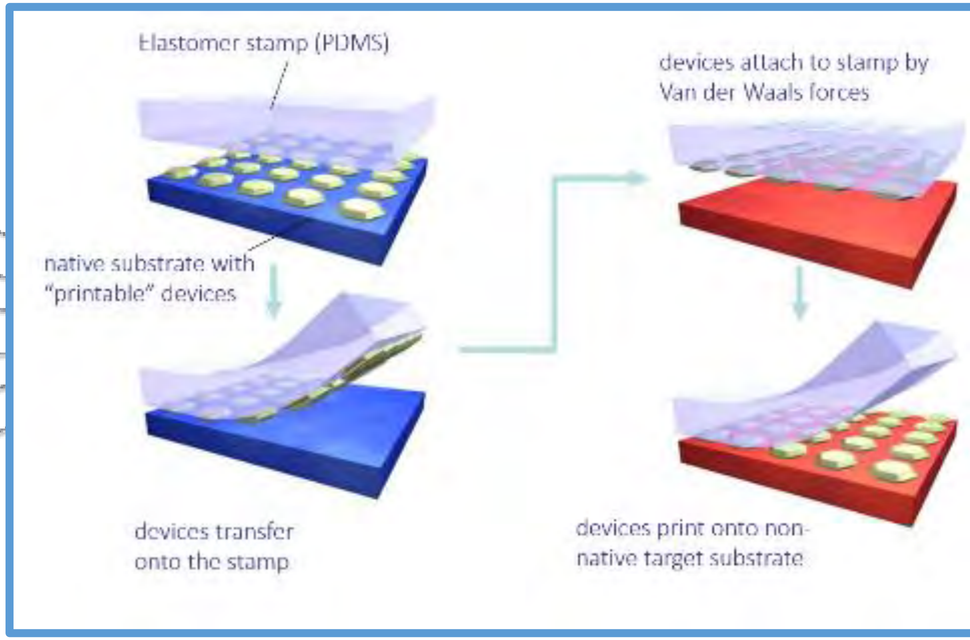
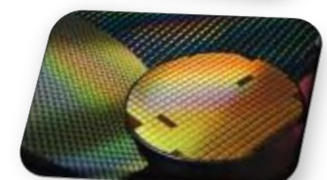
Micro Assembly Unlocks New Opportunities for Wafer Fabricated Devices



Wafer Fabricated Devices
Single-crystal
Fine lithography
(ICs, LEDs, Lasers, etc…)

Elastomer Stamp "Micro-Transfer Printing" (µTP)





The promise of <u>high-performance</u> devices <u>anywhere</u>

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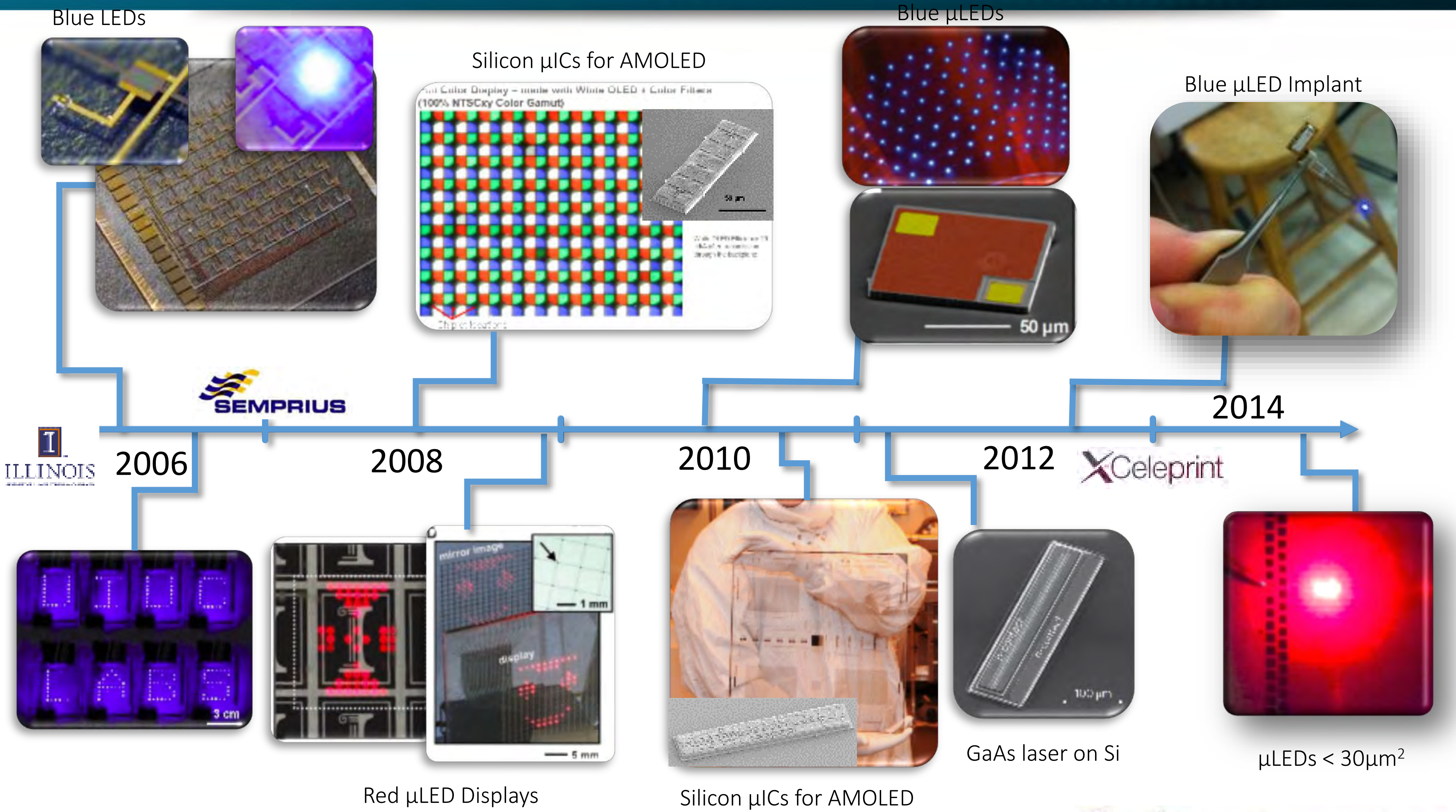
Over a decade of continuous development in micro-transfer-printing



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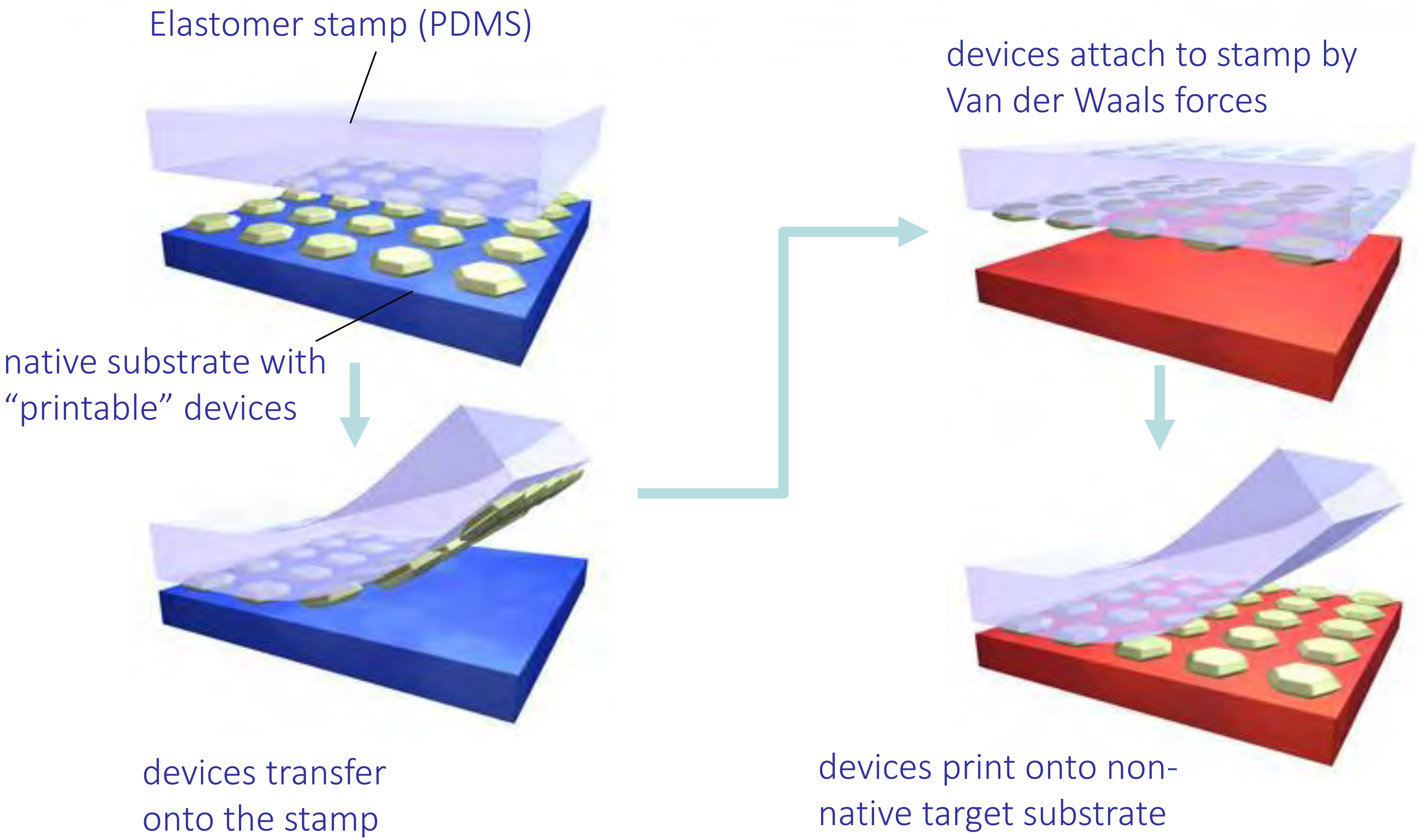
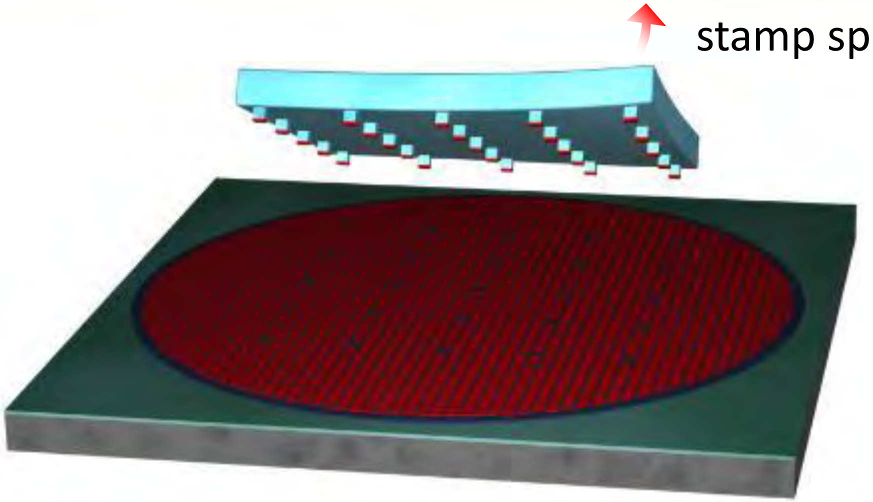
Micro assembly with an elastomer stamp



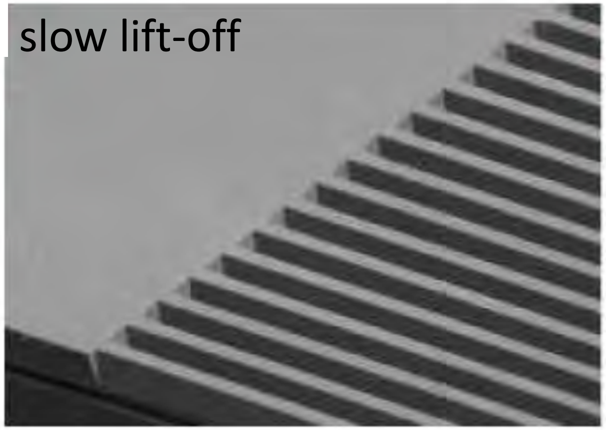
Nature Mater. **5** 33-38 (2006)

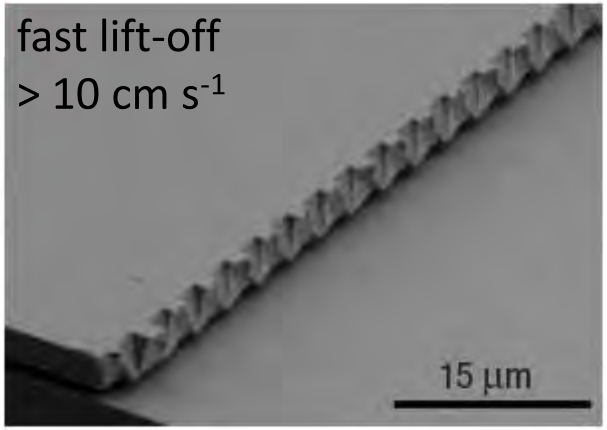
Tunable adhesion

stamp speed controls the elastomer-solid adhesion



"The adhesion between the solid objects and the stamp is rate-sensitive owing to the viscoelastic behavior of the elastomer"

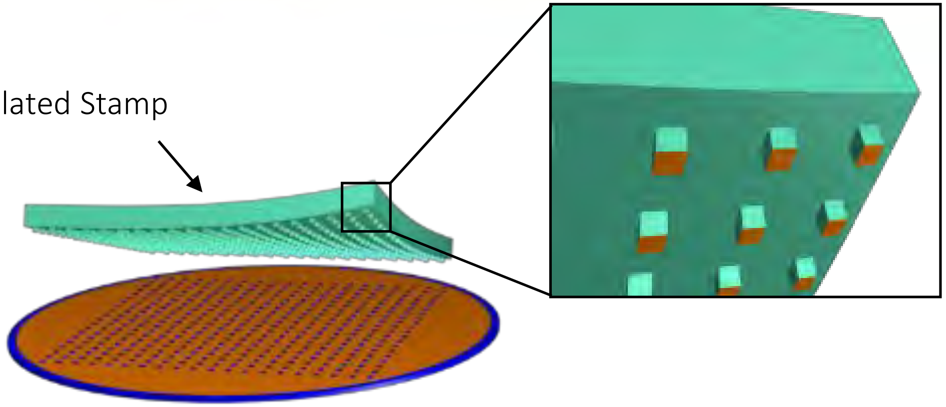


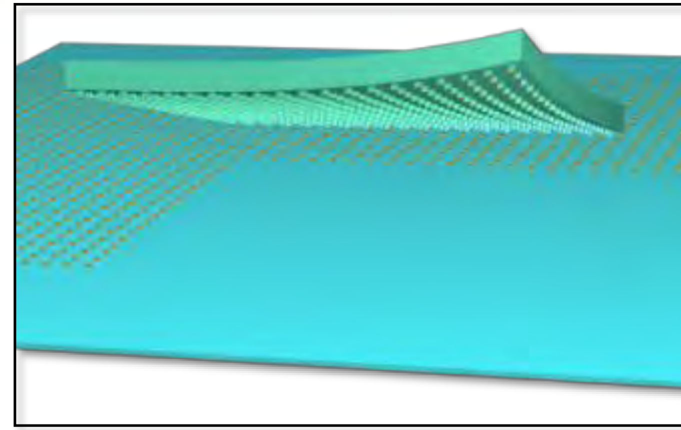


M. A. Meitl et al. *Nature Materials*, **5**, 33 (2006)

Precise dispersal of micro devices from dense arrays by micro assembly

Populated Stamp





Source Wafer

Densely packed micro components

Printing

Non-native "Target" Substrate

Dispersed micro components

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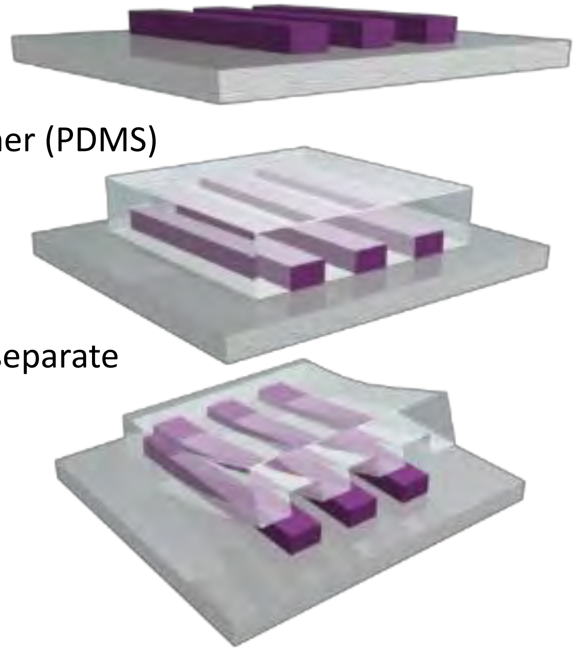
Stamps for micro assembly

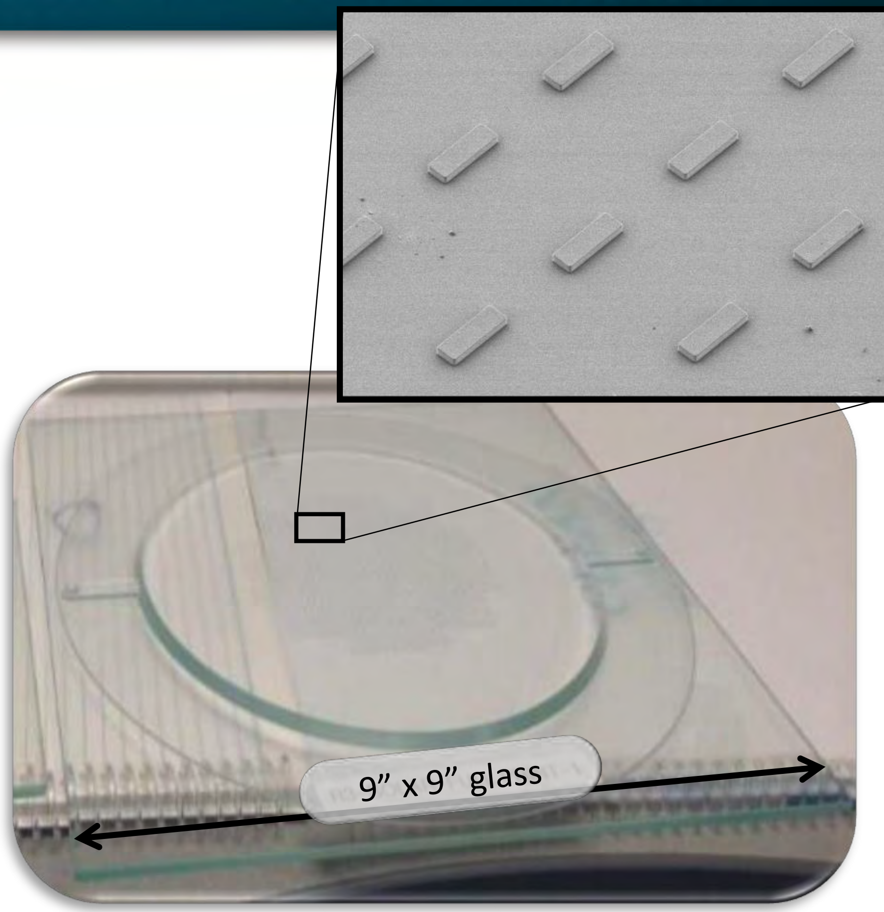
i. Prepare master, e.g. by photolithography

ii. Cast prepolymer (PDMS)

iii. Cure stamp; separate from master

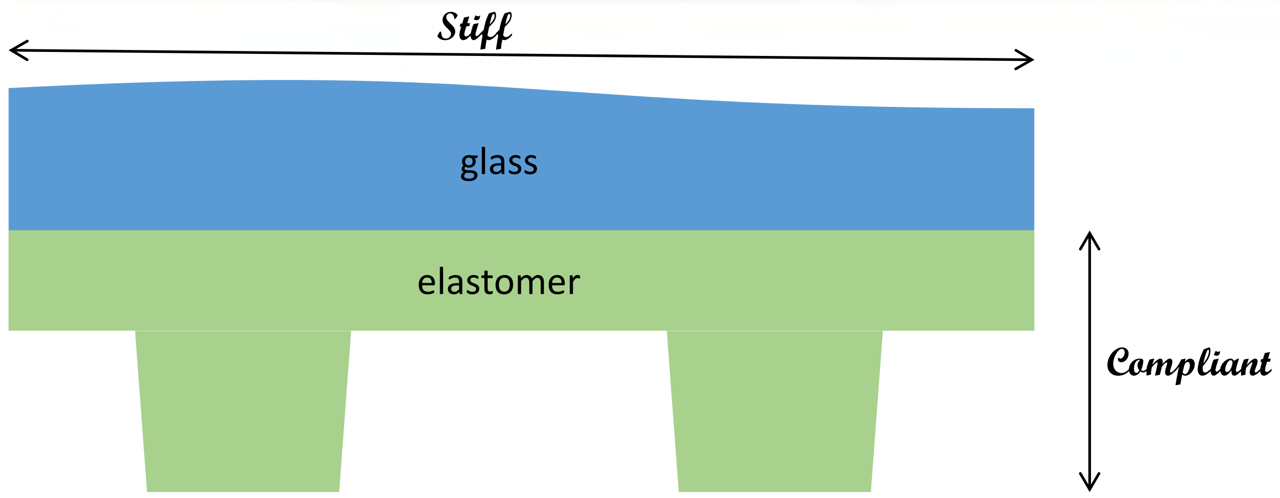


SEM micrograph stamp surface



Transfer stamps are fabricated by casting the elastomer (PDMS) against a microfabricated master wafer.

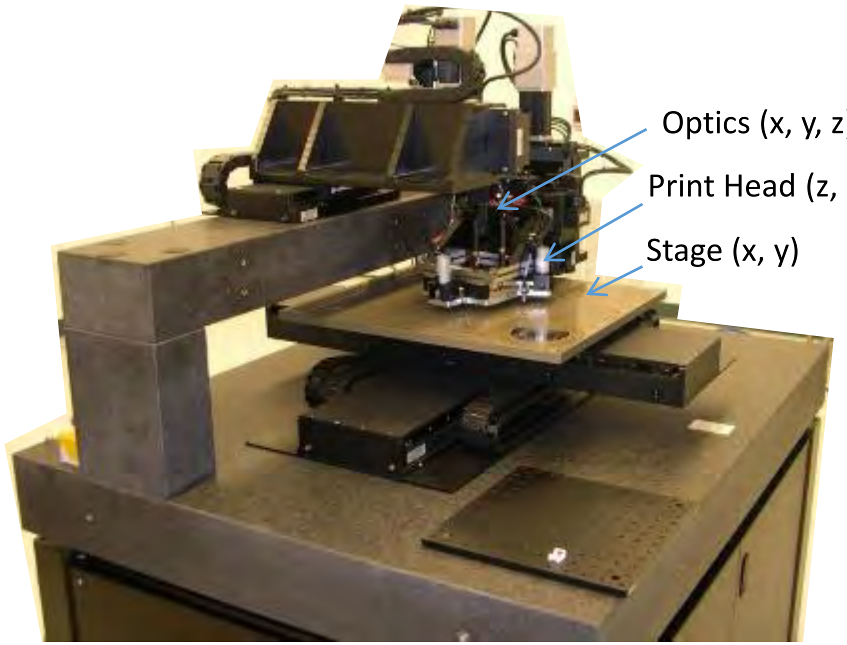
The transfer element → many natural benefits

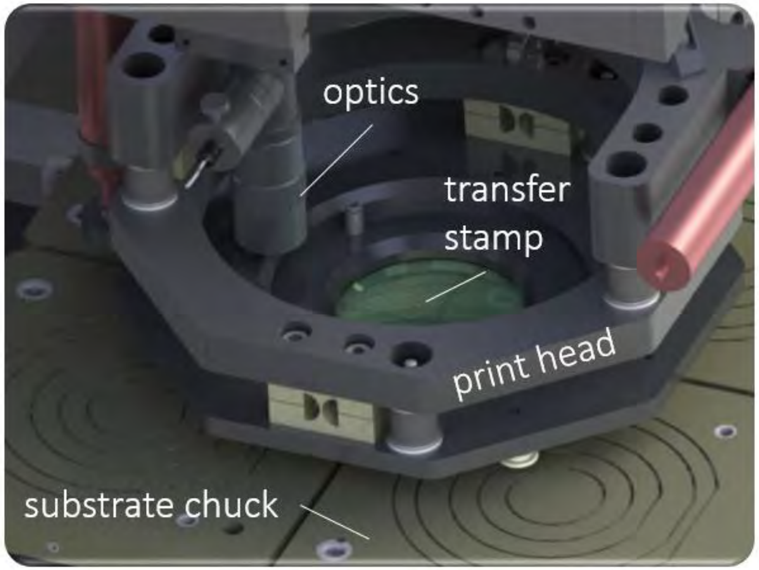


- Naturally compliant in the Z dimension → facilitates contacting real-world surfaces over large areas
- Soft contact → ideal for handling fragile & thin semiconductor devices
- Laterally stiff → maintains registration between transferred devices
- Naturally transparent → facilitates simple & accurate optical alignment during printing
- Low cost → inexpensive materials (glass & silicone) and injection molding fabrication
- Scalable → 150mm active area stamps developed. Larger is a matter of engineering, not science
- Robust → experiments have shown > 20,000 print cycles without problems

Automated micro transfer printing

stamp + motion + optics





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Durham, NC

Tyndall, IE

RTP, NC

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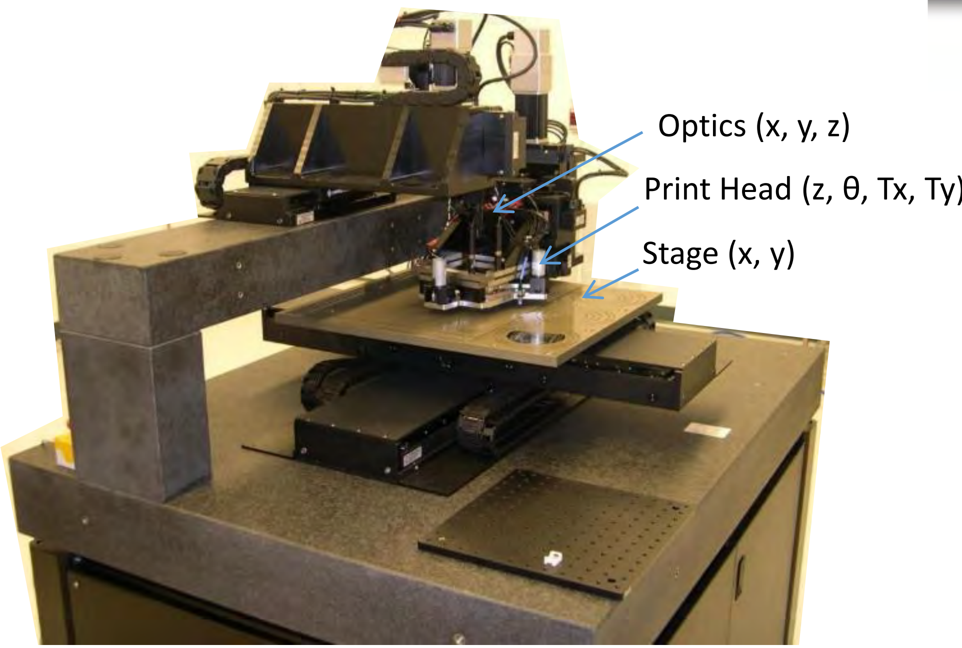
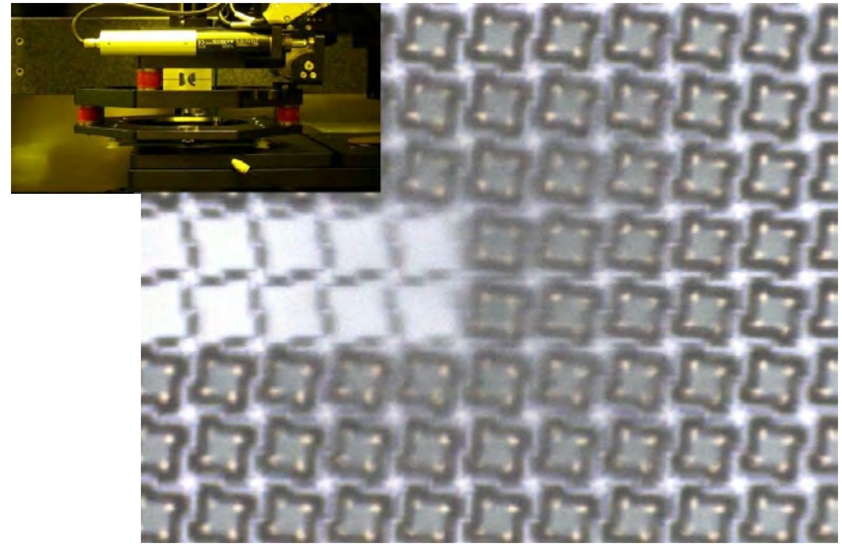
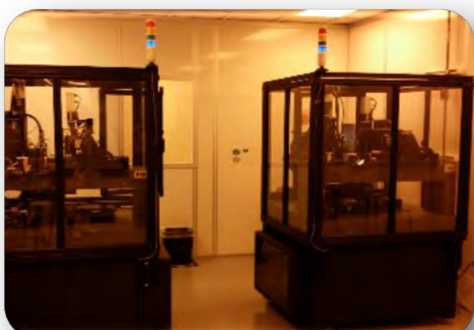
Automated micro transfer printing



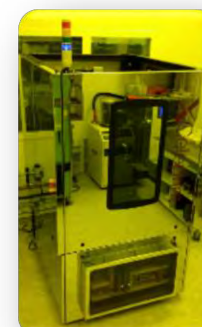




Henderson, NC

Durham, NC

Tyndall, IE



RTP, NC

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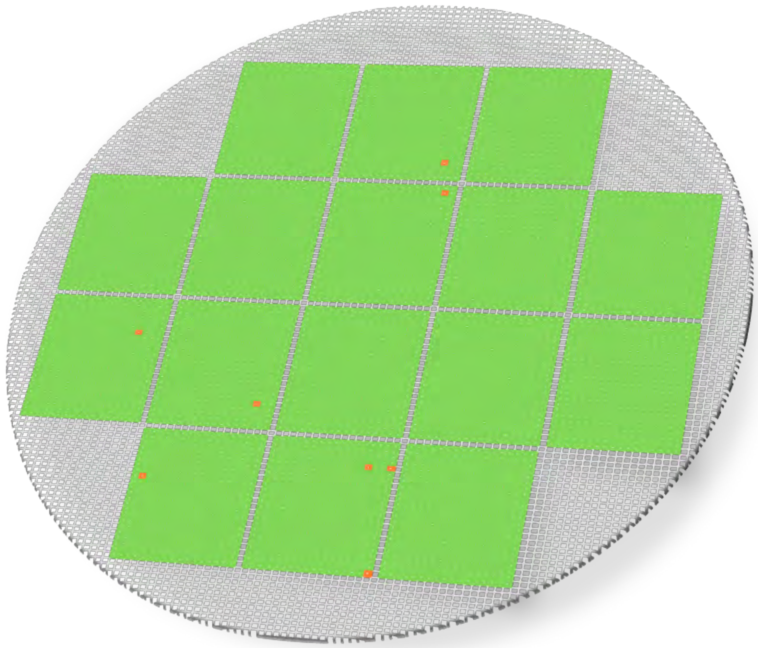
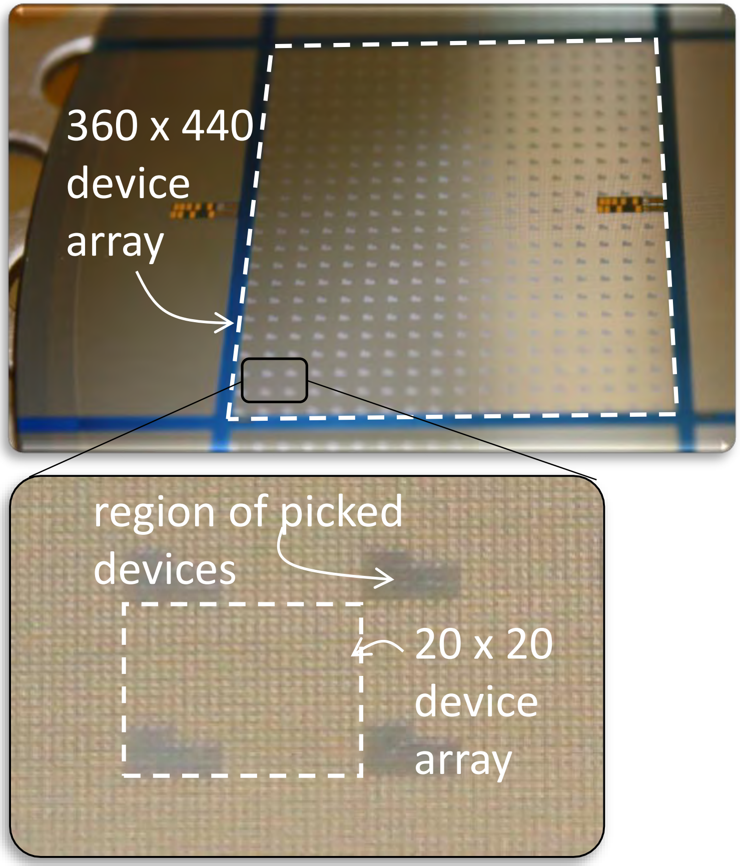
Micro-transfer-printing yields

40µm x 40µm x 1µm GaAs devices printed to a 150mm Silicon wafer



Transfer Print Yield: 12664/12672 (99.9%)
8 minutes to print the wafer
print accuracy +/- 1.5um 3σ

Photograph of the GaAs wafer after ~ 20 print cycles



One 150mm GaAs wafer populates 200 device wafers!

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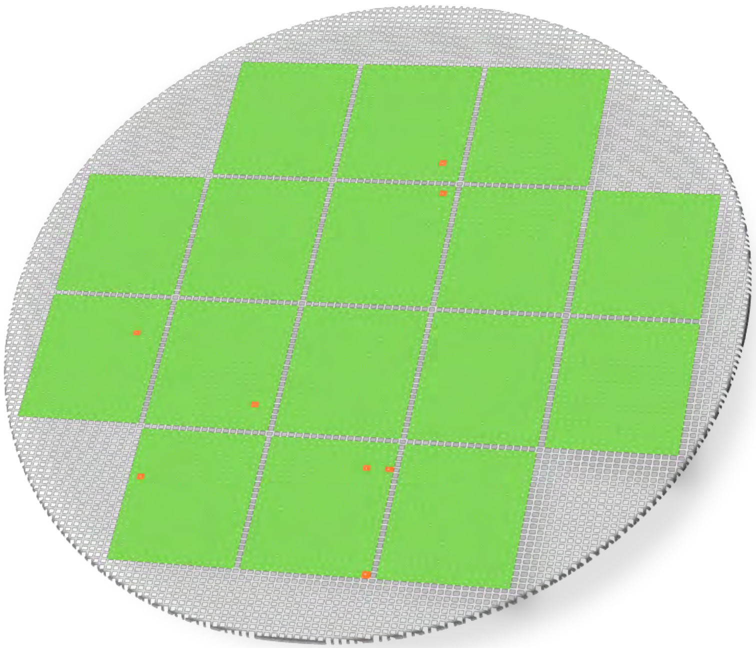
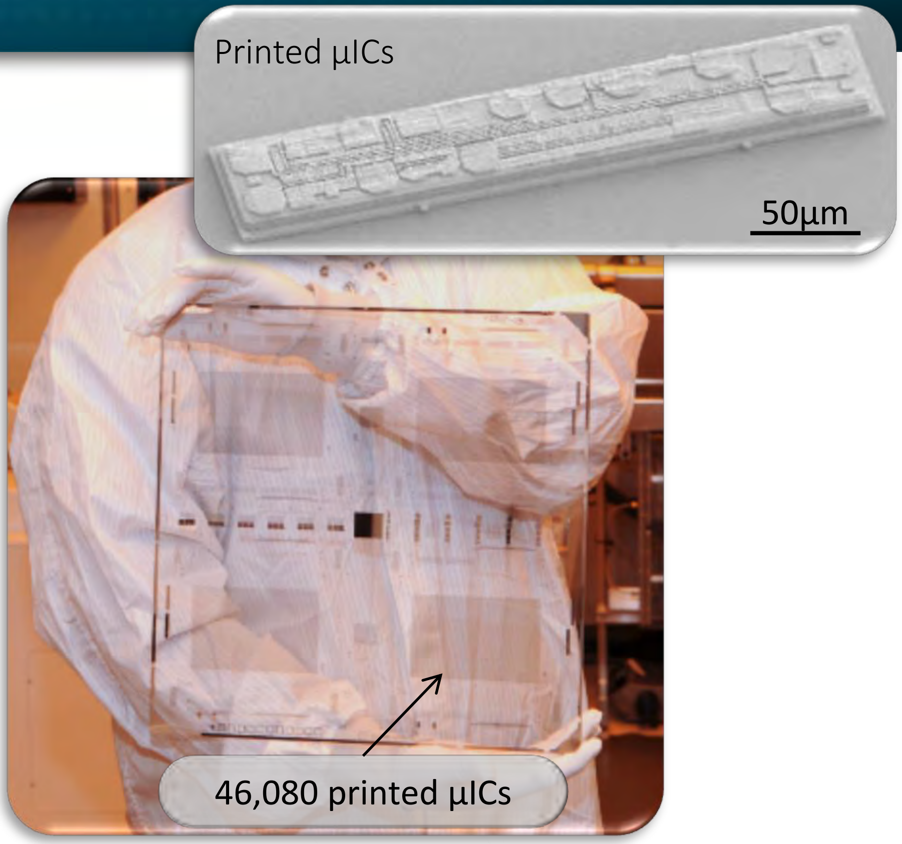
Micro-transfer-printing yields

40µm x 40µm x 1µm GaAs devices
printed to a 150mm Silicon wafer



Transfer Print Yield: 12664/12672 (99.9%)
8 minutes to print the wafer
print accuracy +/- 1.5um 3σ



AMOLED program printed > 2M µICs in 2010:
release & transfer yield > 99.9%
print accuracy +/- 1.5um 3σ

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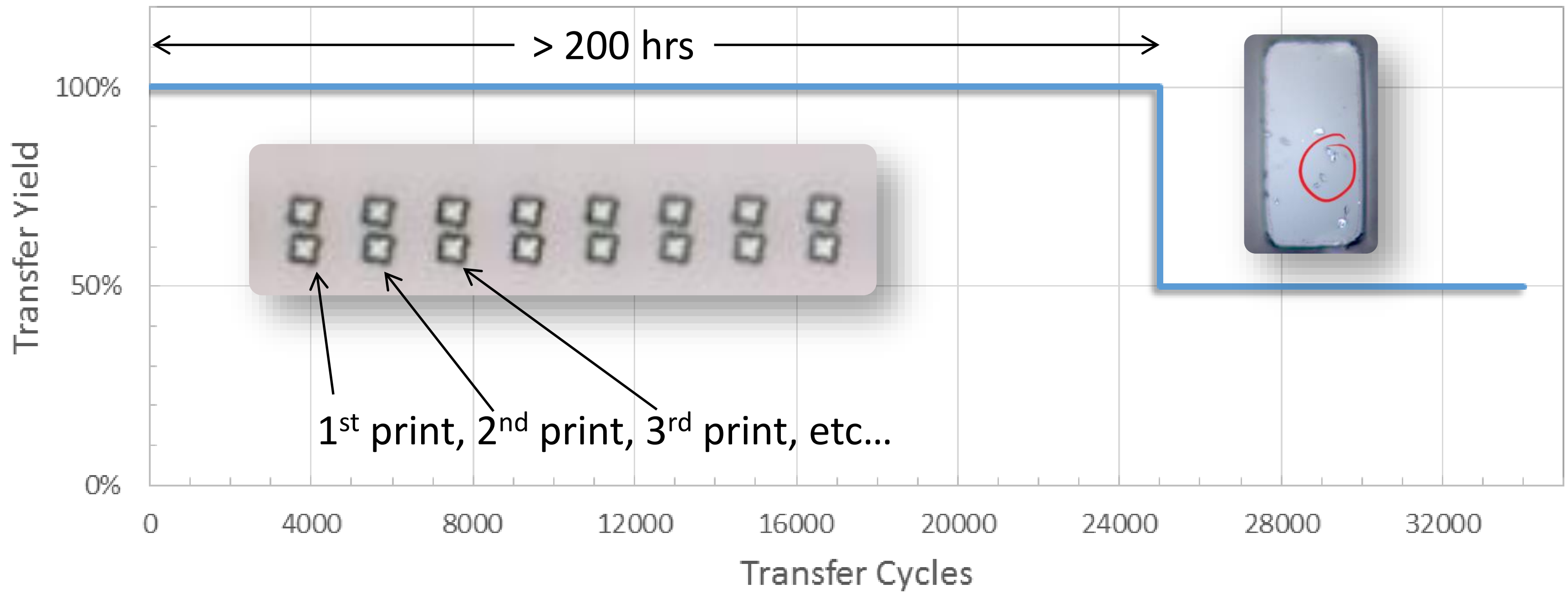
Useful lifetime of the elastomer stamp



Over 25,000 full print cycles without a failure!

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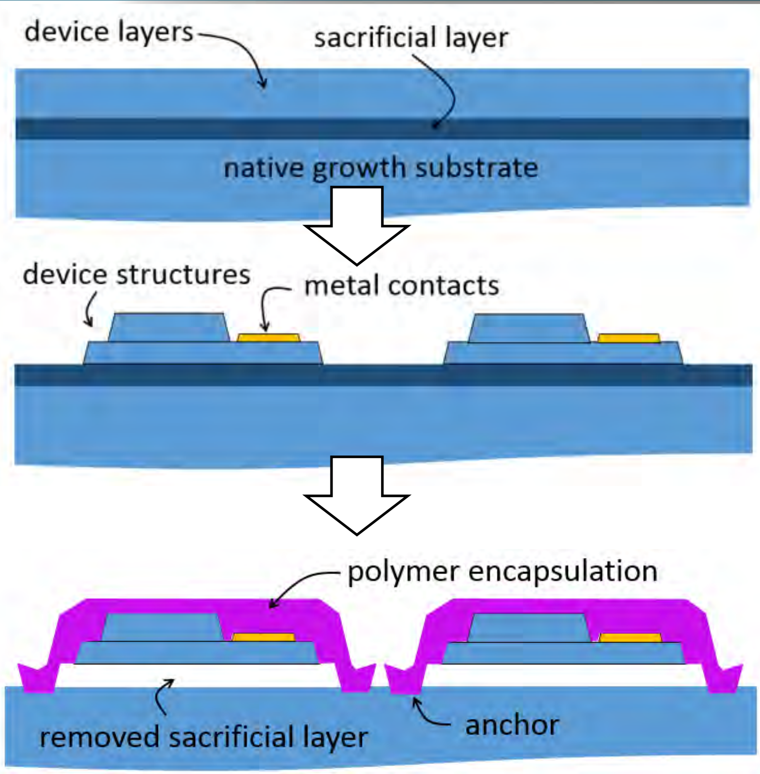
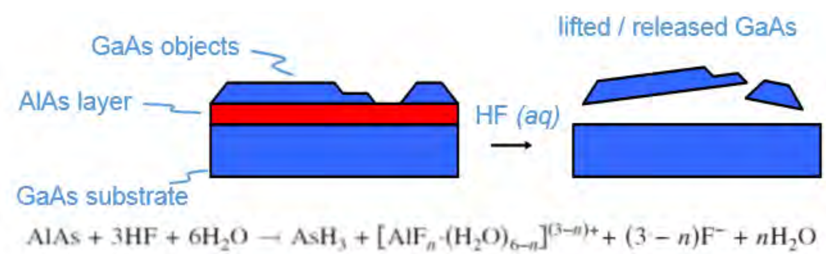
Printable III-V devices

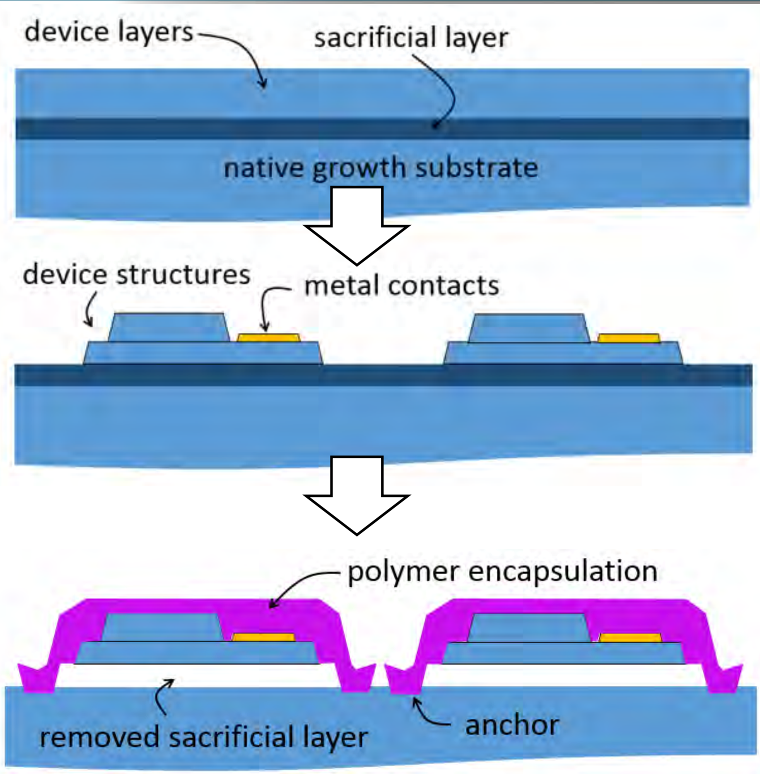


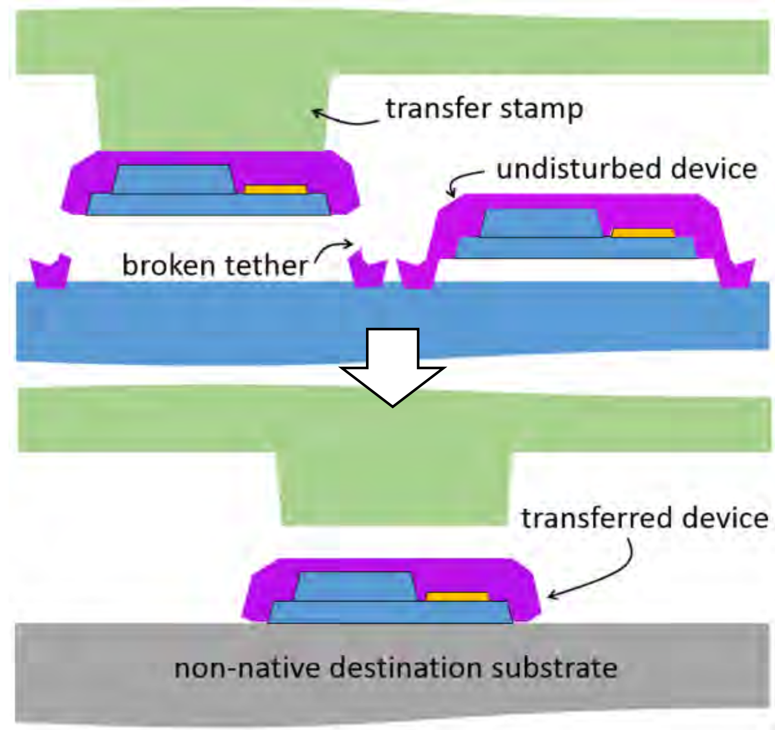
epitaxial lift-off techniques

Lattice matched sacrificial layers provide high-performance devices, and routes to lifting the devices from the native surface.



Printable III-V devices





epitaxial lift-off techniques

elastomer stamp transfer

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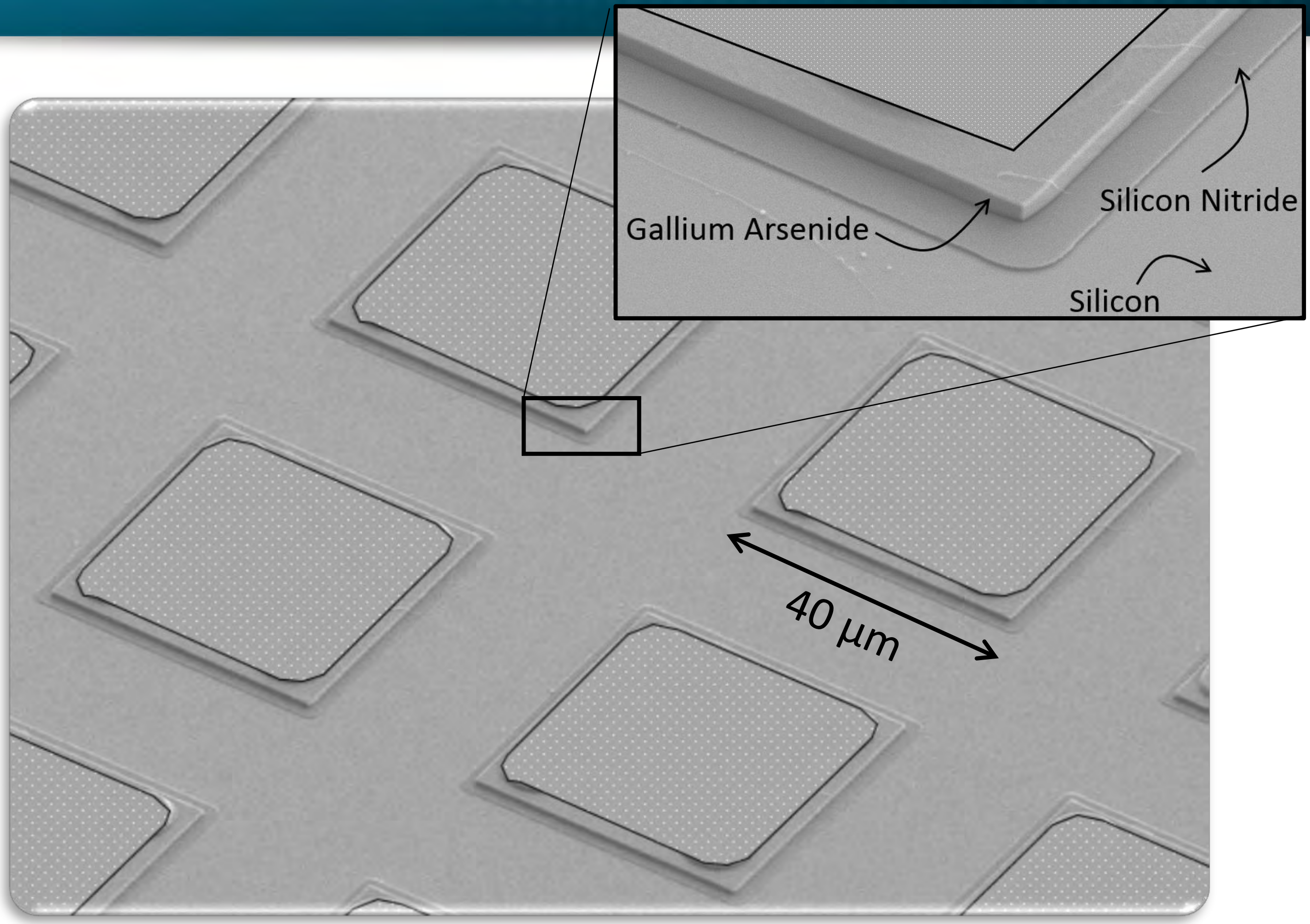
Monolithic-like heterogeneous integration by micro assembly



40 µm x 40 µm x 1 µm GaAs devices micro-transfer-printed to Silicon

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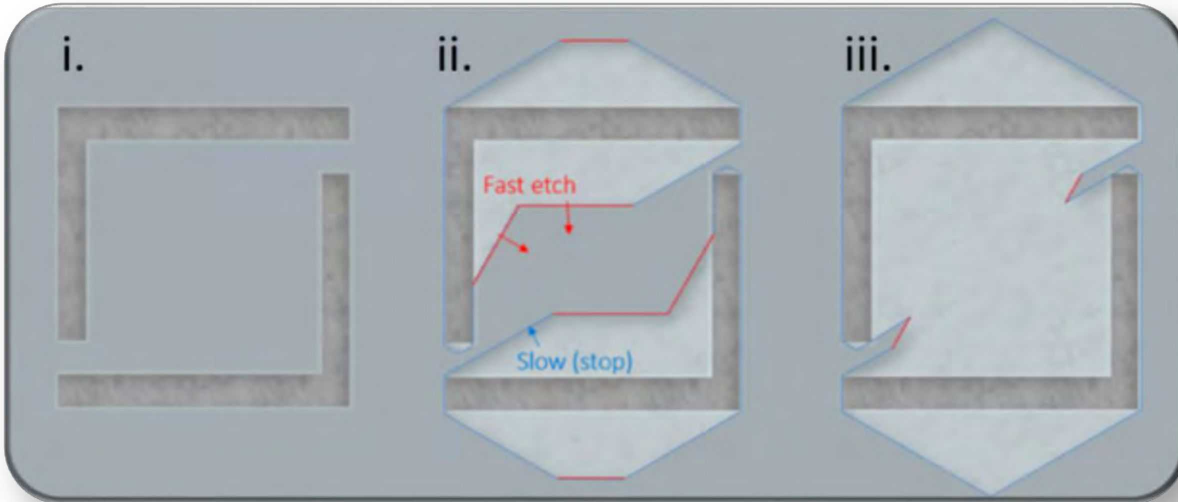
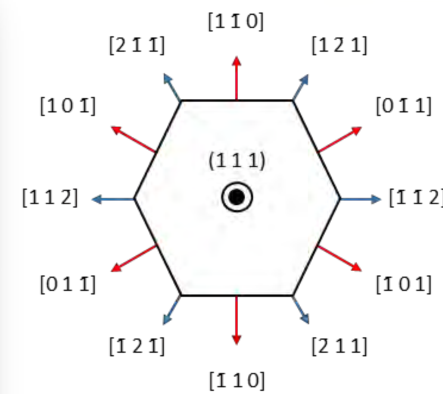
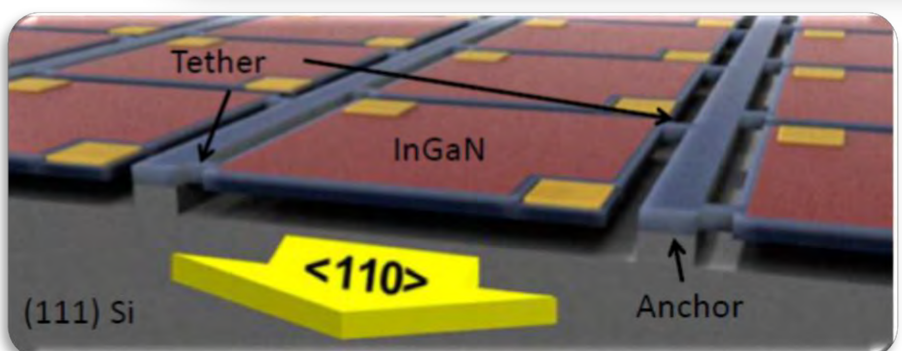
Crystalline release layers

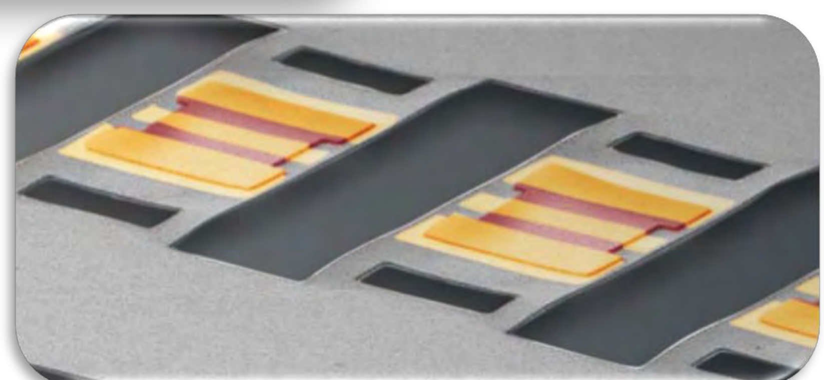
Anisotropic etching of Si (1 1 1) by hot aqueous bases:







Printable Gallium Nitride LEDs [1]



Printable Single Crystal Silicon FETs [2]

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1. *Proc. Nat. Acad. 25, Vol. 108, 2011*
2. 2. *Adv. Funct. Mater.* **2011**, *21*, 3029–3036

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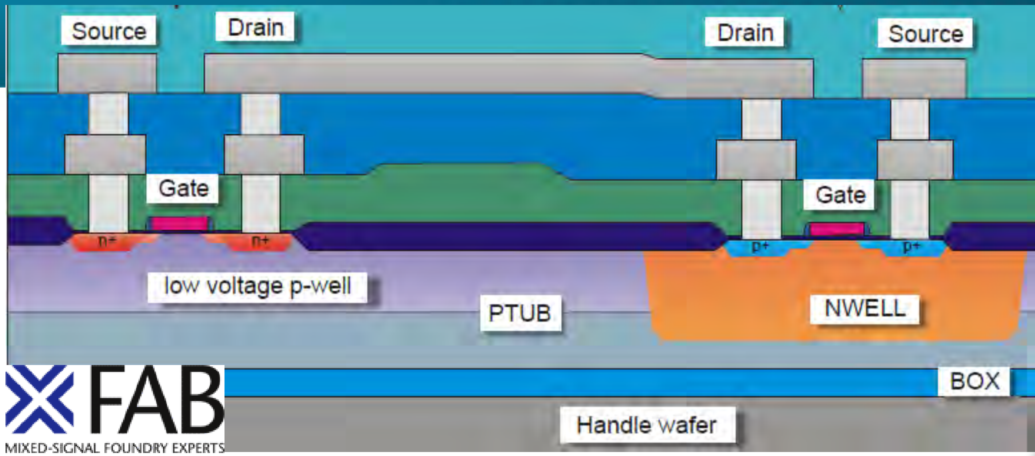
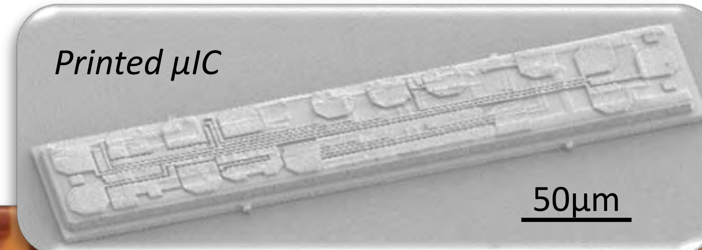
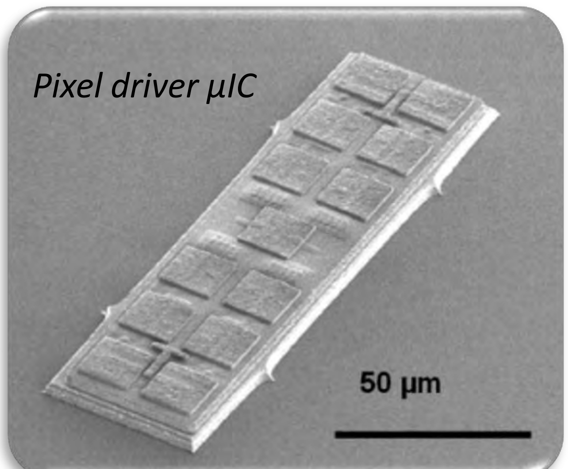
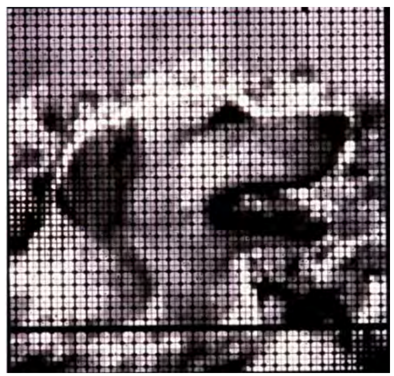
Printable Integrated Circuits

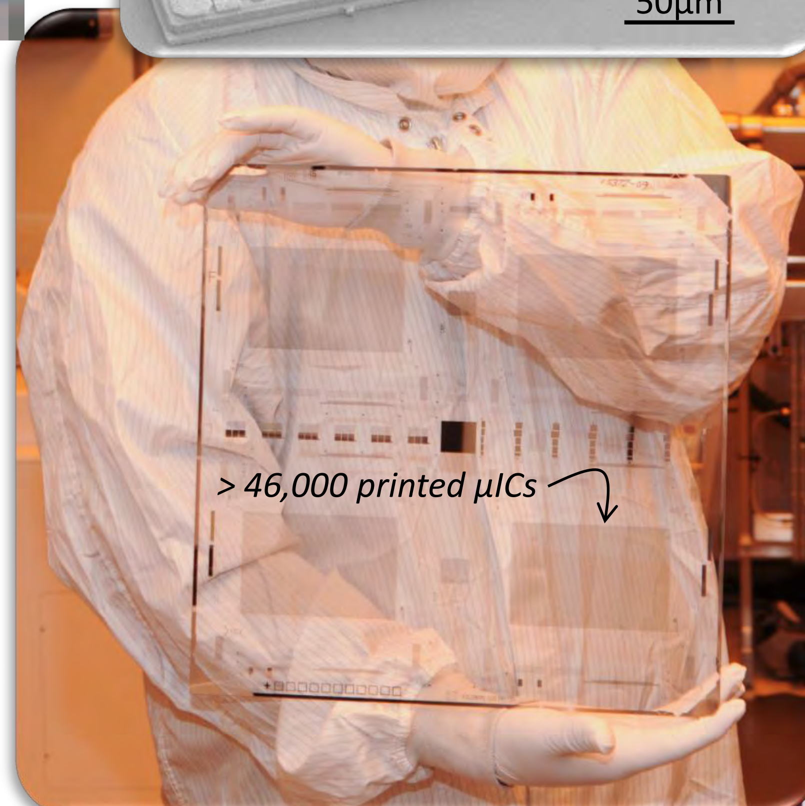


Fabricate CMOS on a SOI wafer and use the buried oxide (BOx) as the sacrificial layer.









C.A. Bower et al., "Active-matrix OLED display backplanes using transfer-printed microscale integrated circuits," *Proceedings of 60th Electronic and Component Technology Conference (ECTC)*, 1339-1343 (2010)

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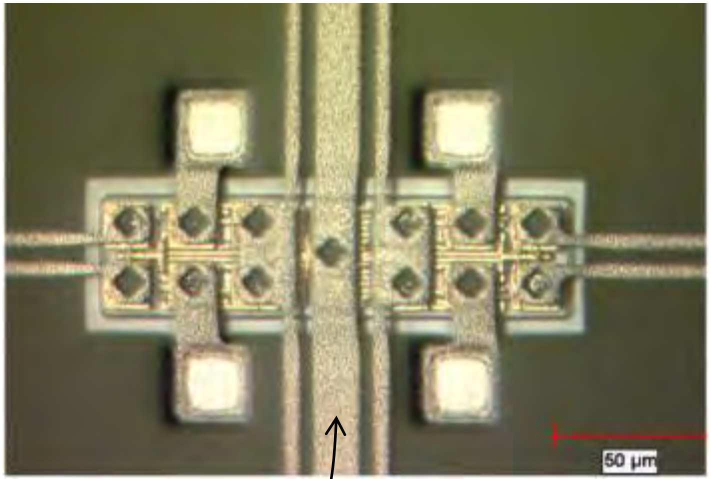
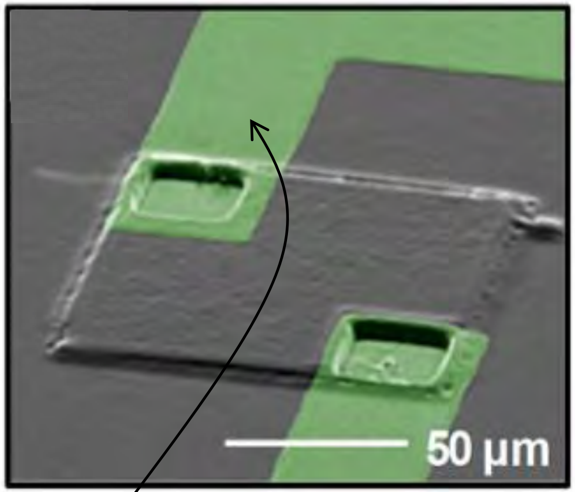
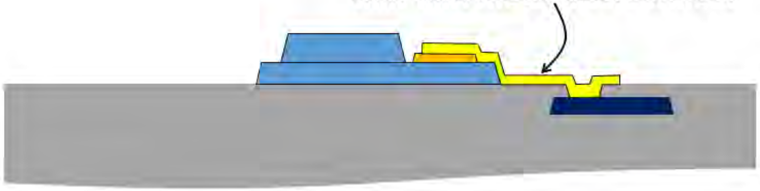
Integrating micro assembled elements



Thin-film metal connecting to a printed micro IC



thin-film metal interconnects to a micro LED



Monolithic assembled elements are electrically integrated using substrate-level metal redistribution lines.

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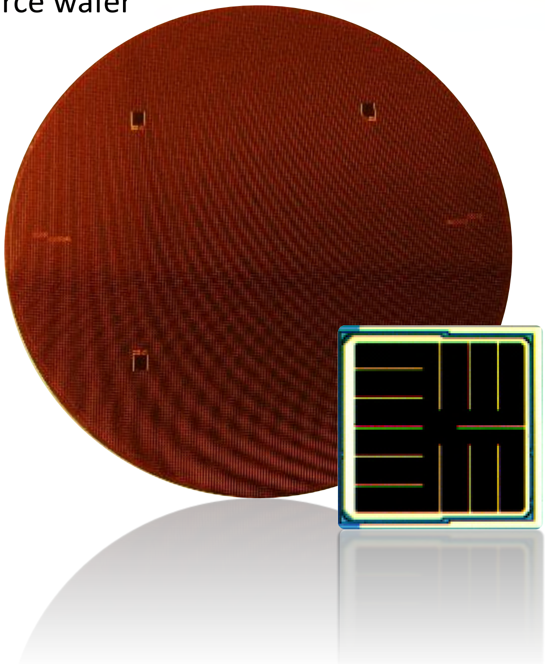
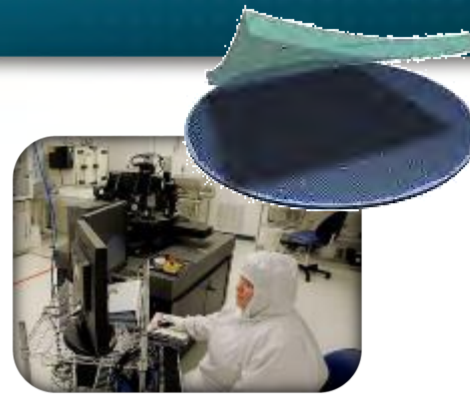
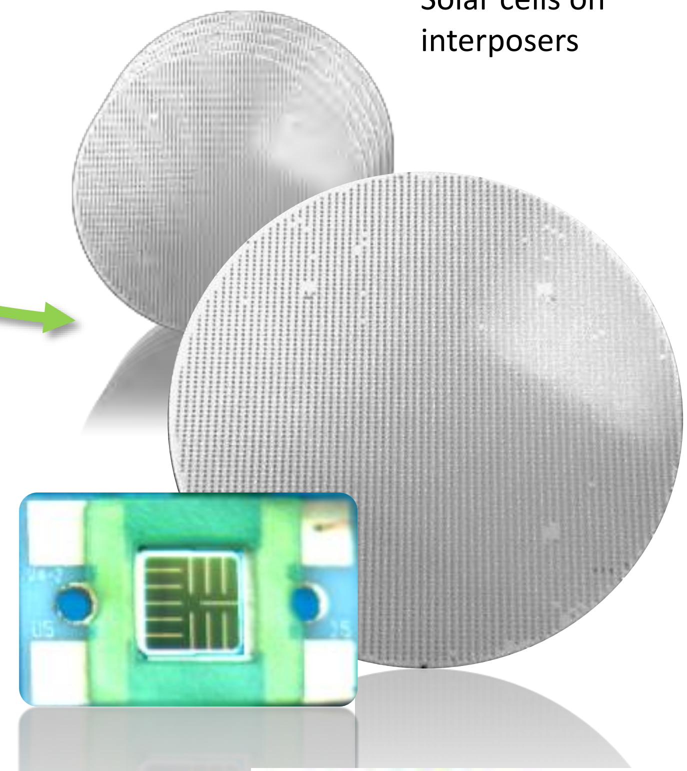
Microscale solar cells

Source wafer





Solar cells on interposers



Reusable substrate

pilot plant opened in 2012

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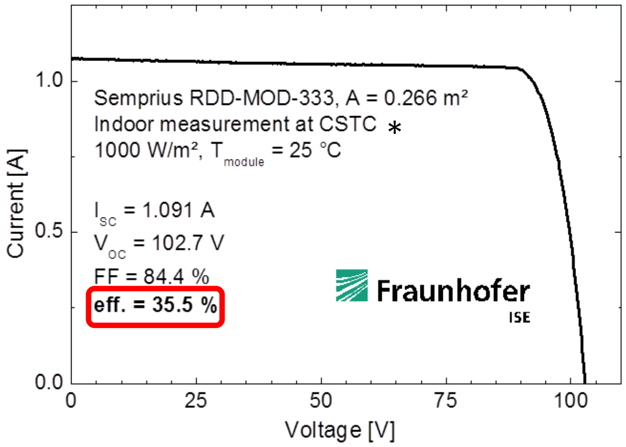
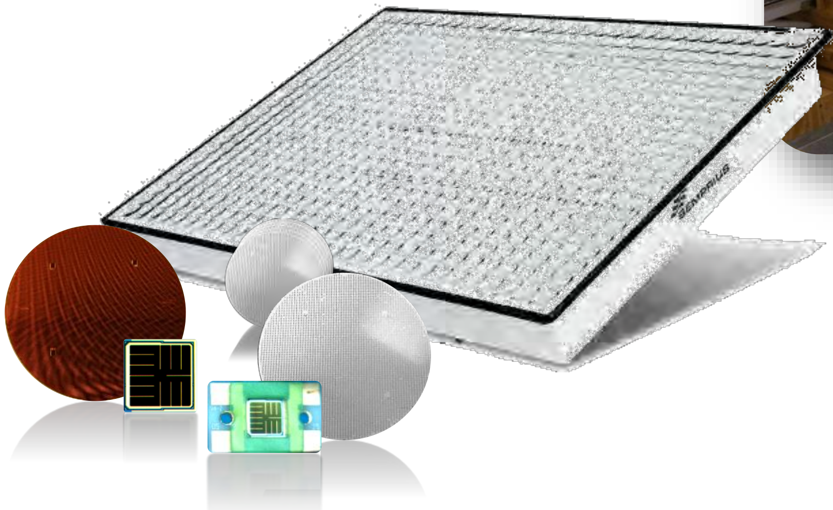
SEMPRIUS

Semprius pilot facility





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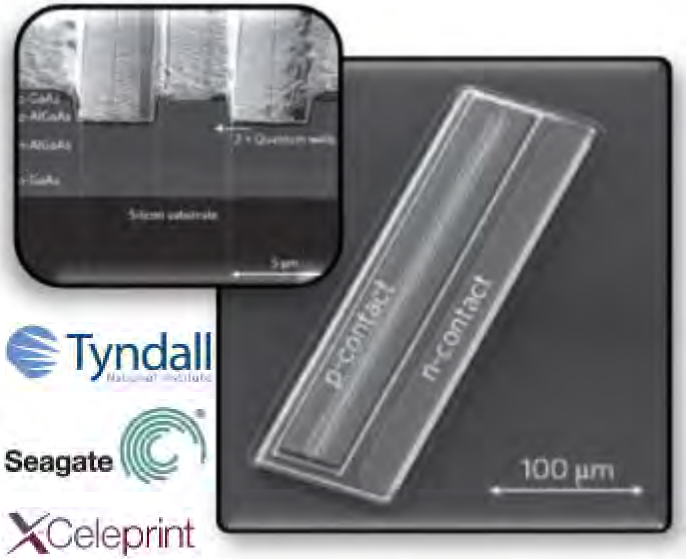
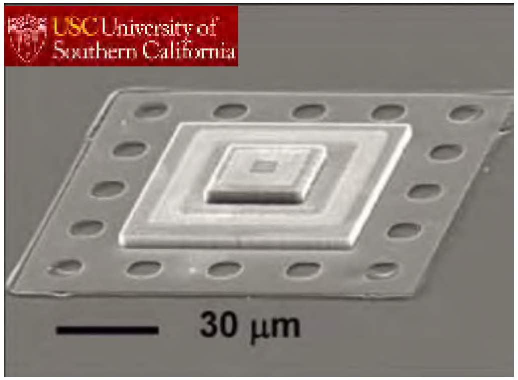
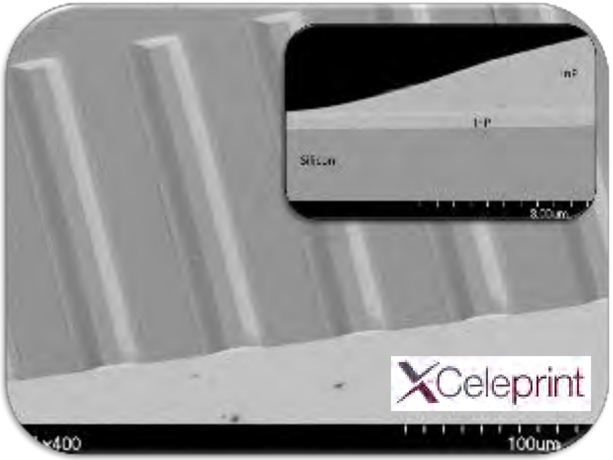
Microscale printed III-V lasers



Etched facet edge-emitting GaAs µlaser on Si [1]



GaAs µVCSELs on plastic [2]



InP laser epi coupon on Silicon

- Edge and vertical emitting lasers have been micro-transfer-printed
- The technologically relevant materials (GaAs and InP) are both well suited for micro-transfer-printing.

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1. Nature Photonics, Vol. 6, pp. 612-616. (2012)
2. Advanced Optical Materials, Vol. 2, 373 (2014)

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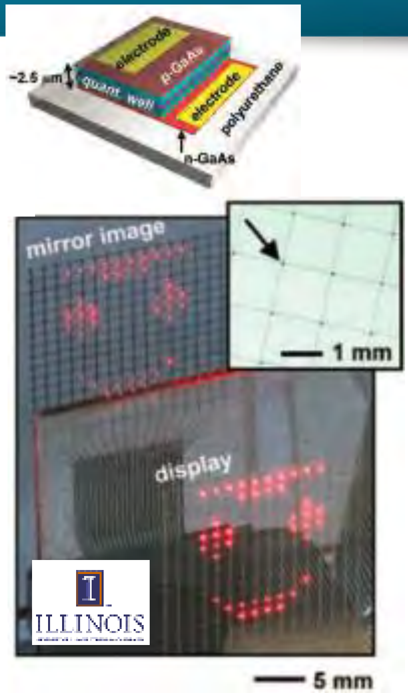
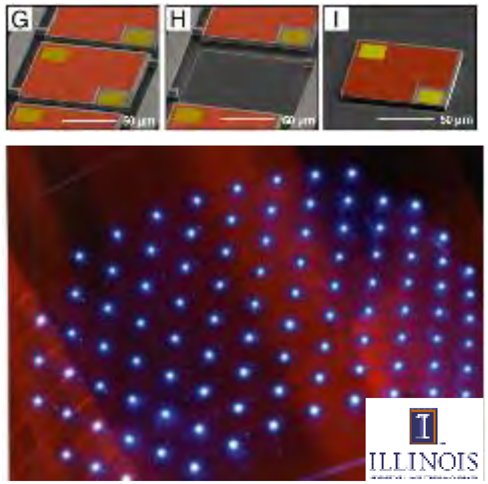
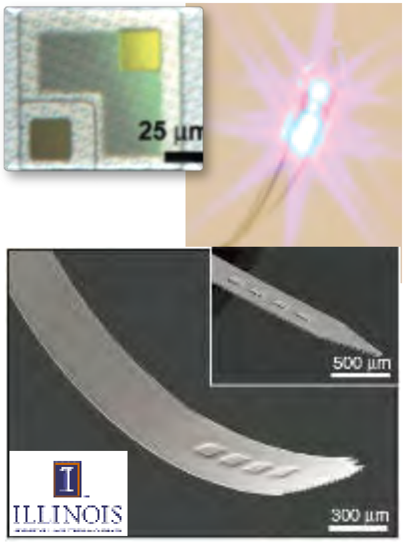
Microscale printed LEDs



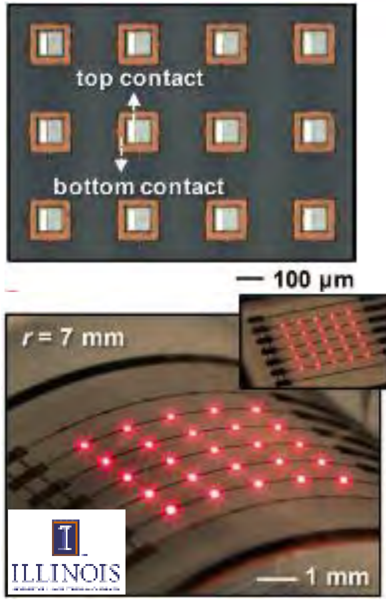
Red μLEDs on plastic [1]



Blue μLEDs on plastic [2]



Blue μLEDs on plastic [3]



Red μLEDs on plastic [4]

- LEDs across the spectrum are printable
- R & D pushing to very small devices

μLEDs < $30 \mu m^2$

1. Science, Vol. 325, pp. 977-981. (2009)
2. Proceedings of National Academy, 25, Vol. 108 (2011)
3. Science, Vol. 340, pp. 211-216 (2013)
4. Small 2012, ***8***, No. 20, 3123–3128

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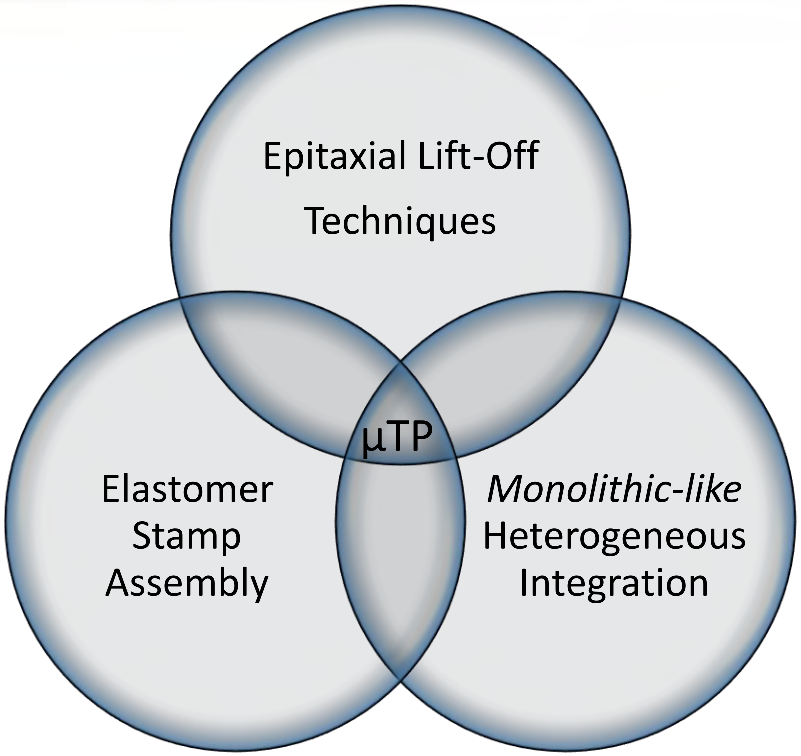
Conclusions

- Modified epitaxial lift-off methods provide printable, high-performance, micro scale compound semiconductor devices
- Elastomer stamp micro assembly provides high throughput, deterministic approaches to precisely disperse the microscale components onto non-native substrates
- Transferred microscale elements can look and behave like monolithic integration
- Robust wafer-level metal redistribution levels are used to interconnect to the transferred devices



μTP = Micro Transfer Printing

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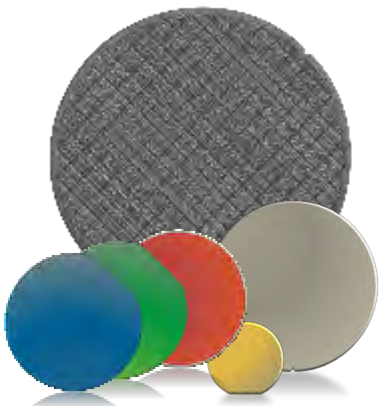
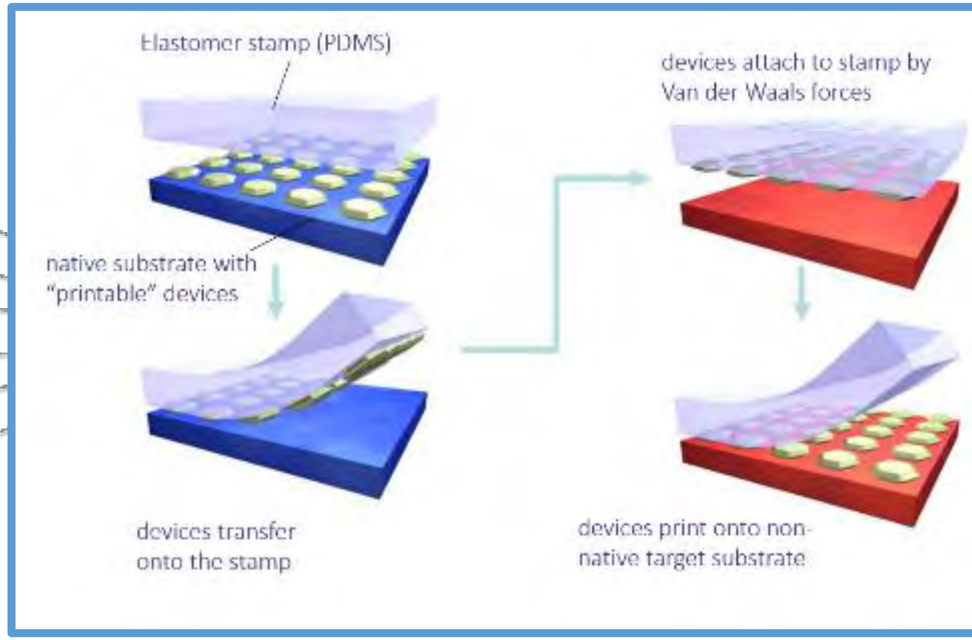
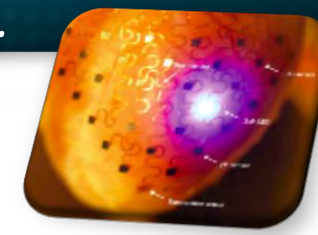
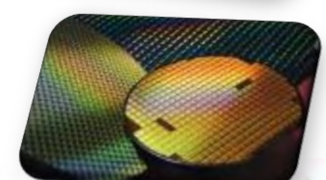
Thanks to the X-Celeprint team.
Thanks to the John Rogers lab at University of Illinois – Urbana-Champaign
Thanks to the technical staff at Semprius, RTI Int'l, and Tyndall Nat. Inst.









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Heterogeneous Integration of Microscale Compound Semiconductor Devices By Micro-Transfer-Printing

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Abstract

Integrating microscale electronic devices onto non-native substrates enables new kinds of products with desirable functionalities and cost structures that are inaccessible by conventional means. Micro assembly technologies are the practical ways to make such microscale heterogeneous device combinations possible. Elastomer stamp micro-transfer-printing technology (µTP) is a widely-demonstrated form of micro assembly, having demonstrated applicability in optical communications, magnetic storage, concentrator photovoltaics and display technologies. Here we describe new experiments designed to assess the useful lifetime of the viscoelastic elastomer transfer stamp, and also describe the methodology and results for heterogeneous integration of microscale compound semiconductor devices onto non-native substrates using µTP.

Introduction

Micro-Transfer-Printing is a broadly-applicable and practical micro assembly technology that was originally conceived and developed in Professor John Rogers' laboratory at the University of Illinois, Urbana-Champaign [1, 2]. The technology has now been under continuous development for over a decade and has played a key role in multiple commercialization efforts.

The key elements of µTP are illustrated in Figure 1. In µTP, an elastomer stamp, typically made of polydimethylsiloxane (PDMS), serves as a carrier to transfer arrays of devices from their native substrate onto non-native destination substrates. The process relies on reversible, differential, and/or switchable adhesion to manipulate arrays of many small, fragile objects [1, 3, 4]. As illustrated in Figure 2, arrays of elastomer posts on the transfer stamps deterministically disperse devices from dense native arrays to sparse arrays on the destination substrates. The transfer process works at room temperature and uses no solvents. It is applicable to almost any destination substrate that has a receiving surface, e.g. glass, ceramics, plastics and other semiconductors.

Merits of the Elastomer Transfer Element

Some of the key benefits of µTP arise from the nature of the transfer element. The elastomer stamp is naturally compliant, allowing it to make physical contact over large areas on substrate surfaces that are not perfectly flat. It is naturally soft, facilitating damage-free transfer of fragile, thin, micro scale devices. The stamp is engineered to be inflexible in the lateral dimensions, minimizing distortion within arrays of printed devices. Earlier work demonstrated that arrays of 46,080 micro scale integrated circuits could be printed with alignment distributions of $\pm$ 1.5 µm 3σ [5].

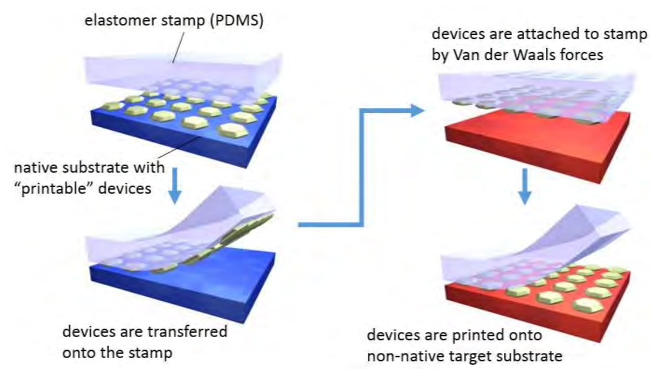

Figure 1. The key elements of µTP (adapted from [1]).

The stamp can include hundreds of thousands of molded posts to manipulate devices in a massively parallel operation and, as illustrated in Figure 2, can precisely disperse arrays of micro scale devices onto the destination substrate. This capability allows the high-performance device elements to be manufactured in dense arrays on their native substrate and then be used in cost-effective sparse configurations on the destination substrates.

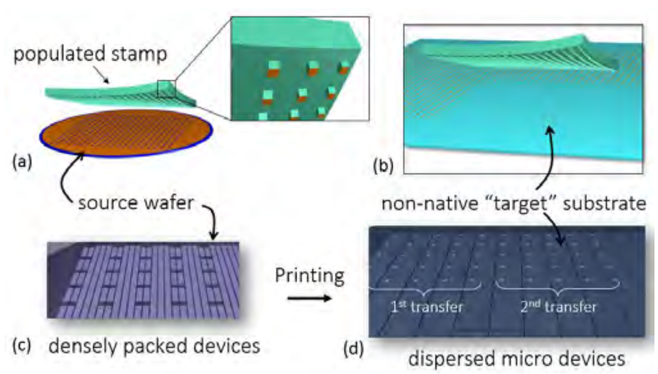

Figure 2. Illustration depicting how a stamp with posts is used to precisely disperse micro scale objects onto a non-native destination substrate.

Additionally, the stamp is naturally transparent, allowing machine optics to look through the stamp to facilitate accurate alignment of the micro devices to the destination substrate. It is inexpensive, made from glass and silicone in a single-step injection molding process. The stamp is also scalable to large sizes, with 150mm scale stamps already demonstrated.

The stamp integrates into simple, highly-scalable motion-plus-optics automated machinery. Figure 3 is an image of the print head. The optics move independently of the print head and are used for alignment, looking through the transparent stamp, during µTP. Existing machinery performs µTP on small to large wafer formats and panels up to 400 mm x 500 mm. Figure 4(a) is a photograph of a µTP tool designed to populate 400 mm x 500 mm panels and Figure 4(b) is a photograph of a tool designed for wafer level µTP.

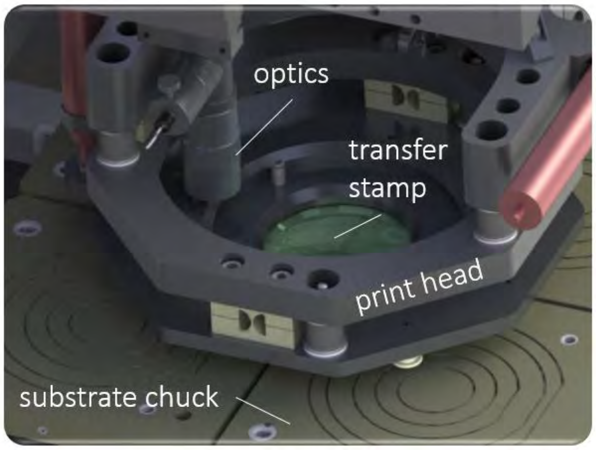

Figure 3. CAD image of the print head.

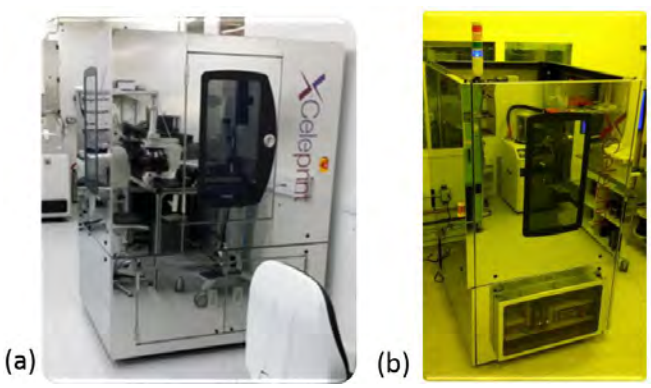

Figure 4. Photographs of µTP machinery.

Soft elastomer stamps have sufficient usable lifetime for high-volume manufacturing schemes that use micro-transfer-printing. Figure 5 illustrates the results of an experiment devised to assess the stamp lifetime. In this experiment, a stamp with a single molded post was used to transfer pairs of 40µm x 40µm Gallium Arsenide devices. The experiment was run in an automated fashion, with the µTP tool operating overnight and over weekends. Ultimately, this experiment showed that the stamp completed over 25,000 device transfer cycles without a failure. Here, the tact time for the transfer cycle was slightly less than 30 seconds, so this experiment represents over 200 hours of printing without an error. The stamp did suffer a repeating failure, due to debris on the elastomer surface, starting at cycle number 25,061.

These data provide evidence that the viscoelastic transfer-print mechanics do not degrade over time and that stamps can be used over industrially relevant time scales. The inexpensive stamps may be considered as weekly, daily or per-shift consumables for a transfer printing operation. Automated optical inspection (AOI) is useful for determining the optimal stamp replacement cycle.

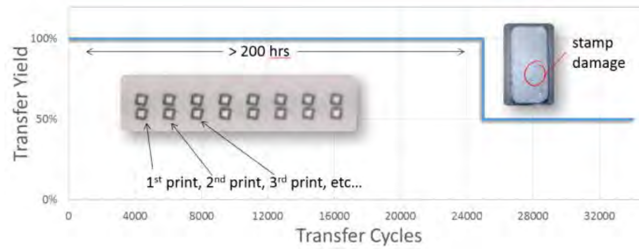

Figure 5. Stamp lifetime experiment.

Printable Compound Semiconductor Devices

Group III-V compound semiconductor materials, such as Gallium Arsenide, Indium Phosphide and their alloys, are used to make high-performance light emitting devices (LEDs and lasers), photodiodes, solar cells and high-frequency transistors. In this section we present a generalized process flow, Figure 6, for making and integrating microscale versions of these high-performance crystalline III-V devices onto heterogeneous non-native destination substrates. Other reports describe processes for making printable microscale Silicon integrated circuits [6, 7] and printable Gallium Nitride microLEDs [8].

As shown in Figure 6(a), the first step is the epitaxial growth of the compound semiconductor layers which comprise the device. A sacrificial layer grown below the device layers, facilitates a modified version of epitaxial lift-off [9] later in the process. When properly designed and lattice matched to the underlying substrate, the sacrificial layer does not increase defect density in the device layers.

Following the epitaxy, the devices are fabricated. Figure 6(b) shows a generic structure representing a compound semiconductor device with etched mesas and metal contacts. The perimeter of the printable device is defined using photolithography and etched down to the sacrificial layer using either wet or dry etching procedures. Following the patterning of the sacrificial layer, a photosensitive polymer is patterned to encapsulate the device, shown in Figure 6(c). The polymer layer protects the device during the subsequent removal of the sacrificial layer and also anchors the released structures to the native substrate. Properly designed anchors prevent the devices from moving during the release process. Finally, the device is rendered printable by selective wet etching of the sacrificial layer, as shown in Figure 6(d).

Figure 6(e) illustrates how the elastomer post of the transfer stamp picks the device away from the native surface. During this operation, the anchoring polymer fractures at specifically designed sections of the polymer which tether the device to the anchor. The stamp post is designed such that the device retrieval process leaves the neighboring devices undisturbed.

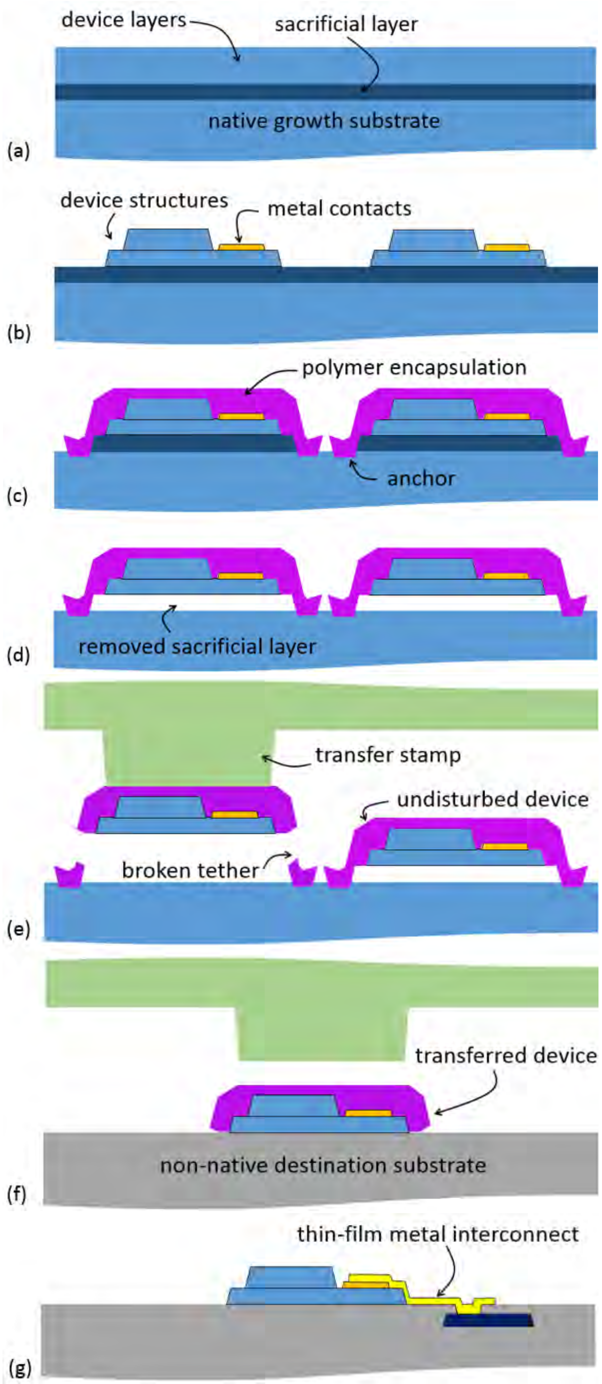

Figure 6. Process flow for making and heterogeneously integrating microscale III-V devices onto non-native substrates.

The stamp, now populated with an array of devices, is translated to the destination substrate. The optics on the print tool, shown in Figure 3, see the devices through the transparent stamp and are used to align the devices to features on the destination substrate. The devices are brought into contact and transferred to the receiving surface, shown in Figure 6(f). The use of thin-film polymers [10] can enhance process yields [5], by planarizing or imparting some degree of conformability to the receiving surface of the non-native substrate. Direct printing, without the polymer receiver, is also practical for smooth surfaces. Figures 8, 11(b) and 11(d) show compound semiconductor devices that are directly printed to Silicon.

Note that the encapsulation polymer prevents contact between the device and the transfer element throughout the entirety of the process. After transfer to the destination substrate, the encapsulation polymer is removed from the device. Figure 6(g) illustrates how the thin microscale devices can then be interconnected using robust wafer-level thin-film metallization processes. Figure 7 shows some previously demonstrated examples of how thin-metallization is used to form interconnects to thin micro-transfer-printed devices [8, 12].

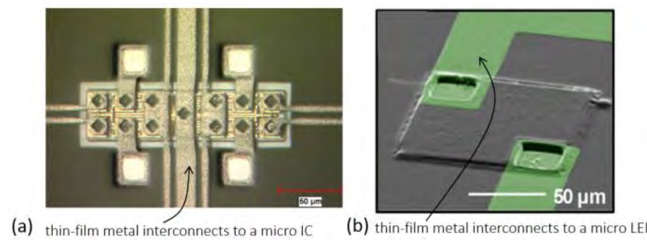

Figure 7. Thin-film metal interconnections to printed micro scale devices; (a) thirteen interconnections to a printed micro integrated circuit (adapted from [12]) and (b) two interconnections to a printed Gallium Nitride LED (adapted from [8]).

Figure 8 is a scanning electron micrograph of 40 µm x 40 µm x 1 µm Gallium Arsenide devices fabricated using the process flow described in Figure 6 and printed directly to a Silicon receiving surface. This image is taken after the encapsulating polymer is removed from the device using oxygen plasma ashing. The inset shows a higher magnification view of this 1 µm thick III-V device printed to Silicon. The Silicon Nitride layer visible in the inset is part of the transferred microscale device.

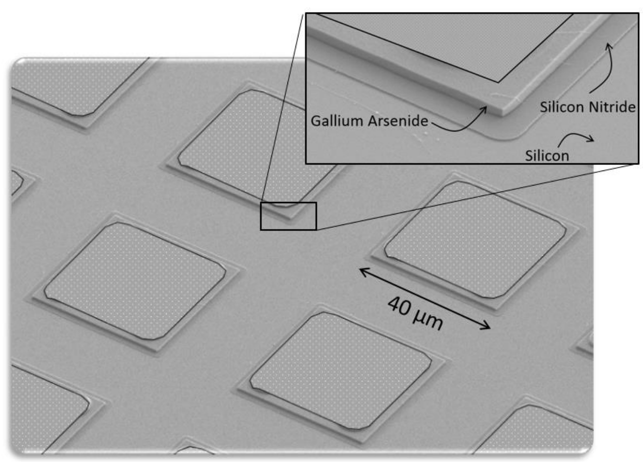

Figure 8. Electron micrograph of 40µm x 40 µm x 1 µm Gallium Arsenide devices printed onto a Silicon wafer. The device surface is obscured to hide design details.

A portion of a 150mm Gallium Arsenide source wafer with print-ready devices is shown in Figure 9(a). In this photo, approximately 20 transfer cycles have already taken place, showing the size and design of the transfer stamp. The stamp has an 18 x 22 array of posts. Each post is designed to transfer a pair of the 40 µm x 40 µm devices. This region on the source wafer contains a 360 x 440 array of devices. Figure 9(b) is a close-up view of the source wafer, showing a section where a 2 x 2 post array has already performed approximately 20 transfer cycles. There are 400 devices in the highlighted section of Figure 9(b), which appears as a rectangle due to the angle at which the photograph was taken.

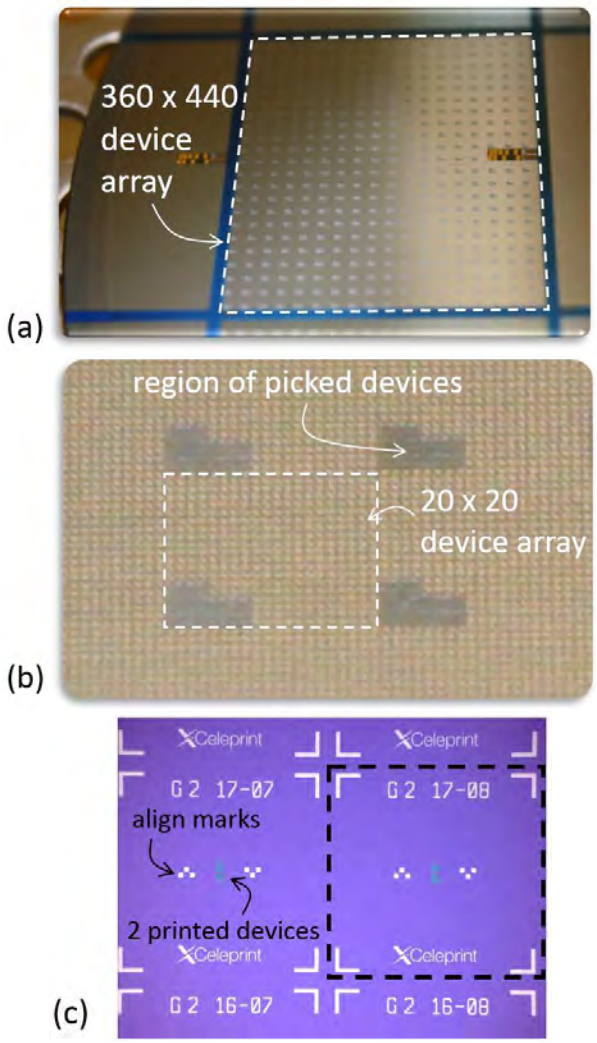

Figure 9. (a) Photograph of a Gallium Arsenide wafer with print-ready 40 µm x 40 µm Gallium Arsenide devices. (b) a close-up of the photograph highlighting the 20 x 20 device array that will be picked up from a single post during 200 print cycles. (c) Optical micrograph of the destination wafer showing the single pair of micro devices printed on each product die.

Figure 9(c) is an optical micrograph of the destination substrate with printed devices. In this example, a single pair of the 40 µm x 40 µm devices is integrated onto each product die. This is a clear illustration of how the patterned stamp can cost-effectively map the devices from their densely packed state on the native wafer onto sparse product configurations. In this example the area magnification ratio is 200x, in other words, the area highlighted in Figure 9(a) will populate 200x that area on the destination substrate.

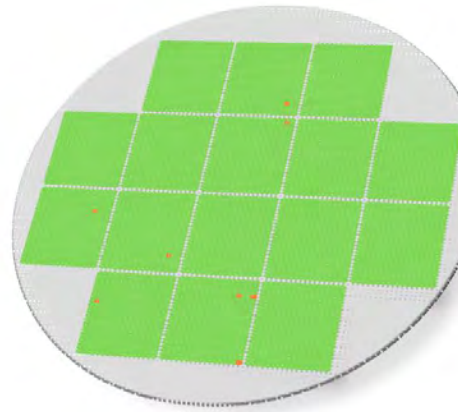

Figure 10. µTP yield for 40 µm x 40 µm x 1 µm Gallium Arsenide devices printed to a 150 mm destination wafer.

Figure 10 shows a transfer yield map of the 40 µm x 40 µm x 1 µm Gallium Arsenide devices printed onto a thin-film polymer coated 150mm destination wafer. Here, each green block is a single printed region, approximately 24 mm x 29 mm in size. The transfer stamp has an 18 x 22 array of posts, and each of the posts transfers a pair of devices. So each print operation transfers 792 devices. Each print cycle requires just under 30 seconds, so it takes approximately 8 minutes to perform the 16 prints necessary to populate this wafer. In this example, 8 devices out of 12,672 did not transfer, representing a µTP yield better than 99.9%.

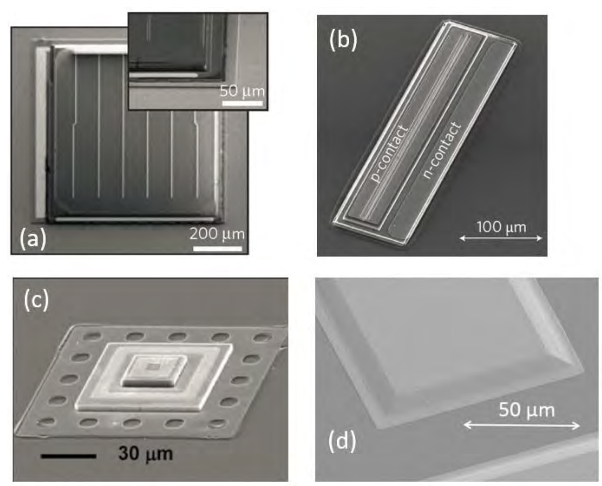

Figure 11. Recent demonstrations of micro-transfer-printed materials and devices; (a) a vertically stacked four junction solar cell (adapted from [13]), (b) an etched-facet edge-emitting GaAs laser on Silicon (adapted from [11]), (c) a GaAs VCSEL on plastic (adapted from [14]), and (d) InP on Silicon.

Figure 11 highlights some of the compound semiconductor devices that have been recently demonstrated using µTP technology. Figure 11(a) shows a four junction solar cell, where the top three-junction cell has been transfer-printed onto a lower one-junction cell [13]. Figure 11(b) shows an edge-emitting Gallium Arsenide laser that is directly printed onto Silicon [11]. A micro-transfer-printed Gallium Arsenide vertical cavity surface emitting laser (VCSEL) is shown printed to a plastic substrate in Figure 11(c) [14]. Figure 11(d) is an electron micrograph of an Indium Phosphide coupon directly printed to a Silicon surface.

Conclusions

Micro-transfer-printing with viscoelastic elastomer stamps is a high throughput, high yield and deterministic approach to micro assembly. Here, we showed that the viscoelastic elastomer transfer mechanics do not change appreciably over many thousands of transfer cycles and that the stamps have sufficient usable lifetime for manufacturing.

We also presented a methodology for making printable microscale III-V devices using a modified form of epitaxial lift-off. When integrated onto non-native substrates using advanced micro assembly technologies, these microscale devices appear quasi-monolithic and can be interconnected using mature and robust substrate-level thin-film metal interconnections. Due to the high device utilization and ability to manipulate many devices in parallel, μTP enables new cost scenarios for utilizing compound semiconductor devices in heterogeneous combinations with other substrate and device technologies.

Acknowledgments

The authors gratefully acknowledge the contributions from Professor John Rogers and his research group at the University of Illinois, Urbana-Champaign and also the technical staffs at Semprius, RTI International, and Tyndall National Institute.

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