

# Transfer Printed Heterogeneous Integrated Circuits

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## Abstract

We present a recently invented approach to combine broad classes of dissimilar materials into heterogeneously integrated (HGI) electronic systems with two or three dimensional (3D) layouts. We have developed a process, called transfer printing, to transfer high performance semiconductor materials such as silicon, gallium arsenide, gallium nitride, indium phosphide onto rigid or flexible substrates. One of the objectives of this approach is to enable the fine-scale integration of compound semiconductors (CS) with standard silicon-based integrated circuit technologies, eg. CMOS, to develop high performance HGI electronics systems on rigid or flexible substrates.

## INTRODUCTION

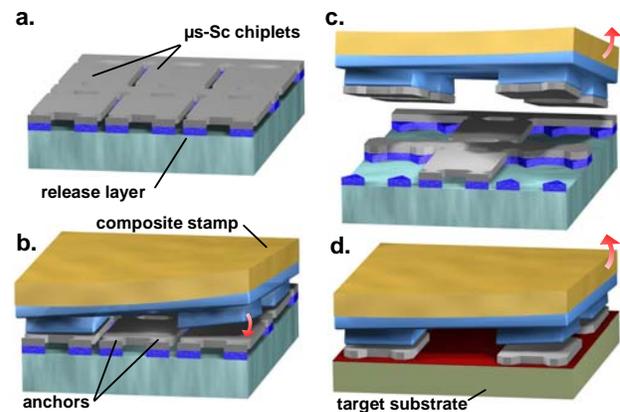
There is a high interest in technologies enabling the 3-D integration of distinct semiconductor layers which are vertically stacked to enable short distance vertical interconnects [1]. Typical applications driving the development of 3-D ICs include 3-D microprocessors [2], stacked memories [3], multifunctional radio-frequency communication devices [4], infrared imaging cameras and addressable sensor arrays [5]. In most cases, a silicon CMOS IC is used for digital signal processing and compound semiconductors provide specific functions such as amplification and preconditioning of high-frequency signals, efficient light emission and detection, or sensing capabilities. Key enabling technologies for the fabrication of 3-D ICs includes aligned wafer bonding, wafer thinning and formation of vertical interconnects [6]. However, many of the 3-D integration processes being developed, like wafer- or chip-scale wafer bonding [7-9] and epitaxial growth [1,10], are not well-suited to integrating compound semiconductors with silicon.

At the University of Illinois at Urbana-Champaign we have developed an approach to transfer high performance single crystal semiconductors onto various substrates, including glass, plastic and other semiconductor materials [11-20]. This transfer printing process is well-suited for fabricating heterogeneous electronic or photonic devices as it is compatible with a wide range of semiconductor materials [15]. Moreover, this process leads to the possibility of improved utilization of compound semiconductor wafer real estate, it can be performed at room

temperature and accommodates semiconductor elements having a wide range of shapes, sizes and thicknesses. Examples of transfer printed semiconductor devices include high mobility silicon thin film transistors (TFTs) [11-14], GaAs metal-semiconductor field-effect transistors (MESFETS) [16,17] and GaN high electron mobility transistors (HEMTs) [18,19]. Semprius is a spin-out of the University of Illinois working to scale-up and commercialize this newly invented transfer printing technology. Herein, we report on the status of the transfer printing technology and discuss some examples of HGI electronic devices fabricated using this technique.

## TRANSFER PRINTING PROCESS

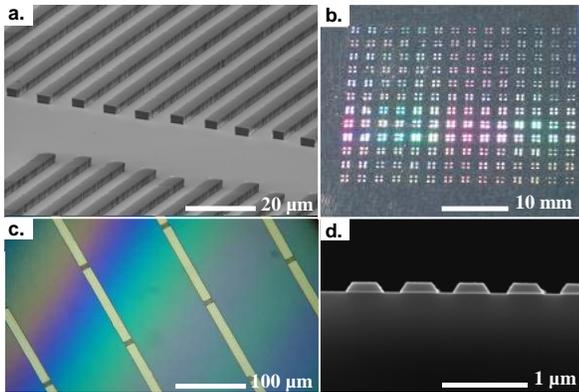
The printing process involves the liftoff and transfer of micro-structured semiconductor ( $\mu$ -Sc) elements from a “mother” substrate to a structured elastomeric stamp, followed by the delivery of these elements from the surface of the transfer stamp to a target substrate [12,20]. Figure 1 schematically illustrates this process.



**Figure 1.** Schematic illustration of the dry transfer printing process.

(a) Single crystal  $\mu$ -Sc chiplets are defined on the surface of a “mother” wafer. (b) A transfer stamp is aligned and then laminated onto this substrate. (c) A fraction of the  $\mu$ -Sc chiplets are selectively transferred onto the raised features of the transfer stamp. (d) The stamp is then brought into contact with a target substrate and then slowly delaminated to enable the transfer of the  $\mu$ -Sc chiplets onto the surface of the target substrate.

By appropriate design of the undercut etch and liftoff of these elements from their mother substrate, it is possible to perform the liftoff step with high yields. This massively parallel printing process can accomplish the transfer of hundreds to several thousands of semiconductor chiplets in each printing step. The transfer relies on van der Waals forces to temporarily bond the chiplets on the transfer stamp and then on the use of an adhesive layer to permanently bond the chiplets on the target substrate. The area of contact between the chiplets and the target substrate must be sufficiently high to enable efficient transfer. In most cases, the dominant requirement is for the bottom surfaces of the elements and the top surfaces of the target substrate to be sufficiently smooth to enable large contact areas. We have found, through extensive studies, that this requirement can be satisfied for a wide range of systems of interest. Figure 2 shows some examples [20].



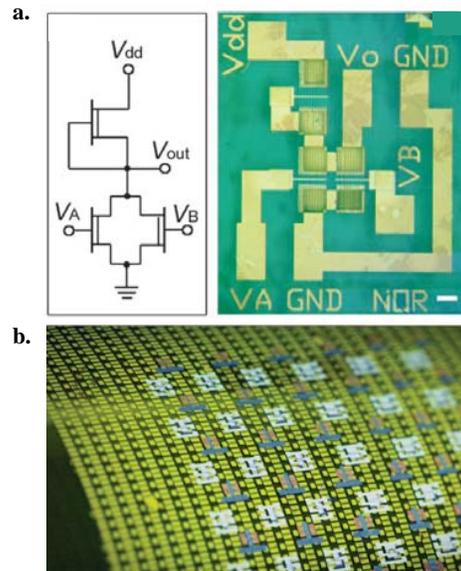
**Figure 2.** Transfer printed  $\mu$ s-Sc chiplets on various substrates. (a) GaN wires transferred on a silicon wafer. (b) Single crystal Si chiplets transferred on a glass substrate. (c) GaAs wires transferred on a silicon wafer. (d) InP chiplets transferred on a silicon wafer.

#### HETEROGENEOUS INTEGRATED CIRCUITS

The process begins with the fabrication of micro-structured elements defined by etching the top surface of standard silicon or III-V semiconductor wafers such as gallium nitride (GaN) or gallium arsenide (GaAs). For GaAs, the process typically begins with formation of a stack consisting of Si-doped *n*-type GaAs, semi-insulating GaAs and AlAs formed on a semi-insulating GaAs wafer by molecular-beam epitaxy (MBE). The AlAs layer provides the ability to lift off the *n*-type GaAs/semi-insulating GaAs bilayer, by use of an HF etchant which selectively removes the AlAs layer. For GaN, a slightly different process has been developed. In this case, the mother wafer consisted of a layer of GaN grown on a silicon carrier. This stack, consists of a layer of undoped AlGaN, a layer of undoped GaN layer and a AlN transition layer on silicon. In this case, an anisotropic etchant of the silicon carrier substrate is used for liftoff.

The transfer printing process, using soft elastomeric stamps, enables the transfer of these micro-structured

elements – or ultimately fully formed MOSFET, HEMT or MESFET devices – onto the surface of a different substrate. Repeating this process over and forming metal interconnection between the stacked layers yields high performance 3D-HGI electronics on rigid or flexible substrates that incorporate any combination of these (or other) semiconductor nanomaterials. Figure 3 illustrates how GaN, GaAs and Si thin semiconductor elements can be heterogeneously integrated on various substrates to form 2D and 3D stacked HGI electronic circuits [15,17]. This versatile methodology can produce a wide range of HGI electronic systems that would be impossible to achieve using standard wafer bonding or epitaxial growth techniques.



**Figure 3.** Transfer printed devices fabricated using compound semiconductor wires. (a) Simple NOR gate circuit fabricated by transfer printed single crystal GaAs MESFETs on a PET substrate. (b) Three-layer stack consisting of GaN HEMTs, Si MOSFETs and single walled carbon nanotube thin-film transistors transferred on a plastic substrate.

#### CONCLUSIONS

In summary, transfer printing of single crystal semiconductor materials has been shown to be an effective means to fabricate HGI electronics. The individual device layers can each be made using standard IC fabrication practices, leading to high performance discrete devices. The room temperature transfer printing process does not add any additional thermal stress into the stacked devices and the patterned transfer stamp allows for high utilization of the compound semiconductor real estate. This approach to device integration allows for sparse integration of high performing elements where needed onto silicon integrated circuits or large panels.

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## ACRONYMS

$\mu$ S-Sc: micro-structured semiconductors  
HGI: heterogeneously integrated  
CS: compound semiconductors  
IC: integrated circuit  
TFT: silicon thin film transistors  
MESFET: metal-semiconductor field-effect transistor  
HEMT: high electron mobility transistor

