

**DNA ASSISTED MICRO-ASSEMBLY:
A HETEROGENEOUS INTEGRATION TECHNOLOGY FOR
OPTOELECTRONICS**

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The integration of optoelectronic and electronic components from different origins and substrates makes possible many advanced systems in diverse applications in photonics. To this end, various hybrid integration technologies including flip-chip bonding, epitaxial lift-off and direct bonding, substrate removal and “appliqué” bonding, micro-robotic pick and place, and self-assembly methods have been explored. In this paper, we will briefly describe and evaluate these approaches for their applications in optoelectronics and focus on a new micro-assembly technology that can pick, place, and bond many devices of different origins and dimensions simultaneously in a parallel fashion on very large surfaces. We will present some of our preliminary results demonstrating the feasibility of this DNA-assisted micro-assembly technique.

1. Introduction:

In the context of hardware development, “Heterogeneous Integration” (HI) techniques refer to a body of processes and methods that are used to bring together in a highly integrated fashion, structures at the chip (circuit), device, or material levels which cannot be fabricated together using conventional processing techniques due to geometric or material incompatibilities. Typically, conventional hybrid integration techniques are used to bring together macro-scale circuits fabricated on chips of different origins to produce, for example, multi-chip modules having high performance or novel optoelectronic capabilities. However, as micro/nanofabrication techniques evolve, new hybrid integration techniques have emerged allowing micro-scale devices, and even the materials which compose individual devices, to be brought together from different origins to build more complex devices and circuits. These techniques are paving the way to the realization of truly heterogeneously integrated chips and circuits.

In general, the process sequence to generate HI chips includes five common key steps including (not necessarily in this order):

- i) the fabrication and testing of the structure of interest on its mother substrate
- ii) the preparation of the host substrate
- iii) removal of the structure of interest from its mother substrate
- iv) the Pick and Place (P&P) process to handle the structure and position it onto the host substrate, and
- v) the grafting step where the structure is attached or bonded to the host substrate.

Generally substrate preparation steps affect the yield of the overall process sequence while the P&P and grafting steps govern the reliability, applicability, and overall cost of the approach. In this paper, we will attempt to break down various previously proposed HI techniques into these steps in order to evaluate relevant figures of merit for each technique. We will use this classification, to show that the missing link for an enormous leap forward in HI is the availability of a high-speed, cost effective P&P process. To

create this link, we will present and demonstrate the feasibility of a new and radically different P&P process, that of DNA assisted micro assembly, and evaluate its potential impact on HI chip fabrication and HI material synthesis for optoelectronic applications.

2. A Review of Existing HI Processes

In the following sections, we will review some of the relevant processes that have been previously developed or are being developed to facilitate HI. We start our review with flip-chip bonding to establish a benchmark that we will reference when we describe newer techniques.

2.1. Flip-Chip Bonding: A Successful HI Technique

Optoelectronic chips employ materials and devices with widely different properties for light detection, generation and modulation, and signal amplification and processing. Over the last decade, flip-chip bonding,¹⁻³ a sequence of powerful HI processes, has quickly become the accepted method to combine these functions in a hybrid fashion. This technique, originally developed at IBM and code named C4 for silicon chip packaging, has been widely adopted by the optoelectronics community to bring together optoelectronic devices and device arrays with electronic circuits. Perhaps, the most exciting utilization of flip-chip bonding in optoelectronics has been its application to focal plane arrays⁴ and to spatial light modulation.⁵⁻⁹ More than one million bumps can be used to hybridize incompatible devices and substrates such as infrared detectors with silicon amplifiers, or GaAs transmitters and detectors with Silicon logic.

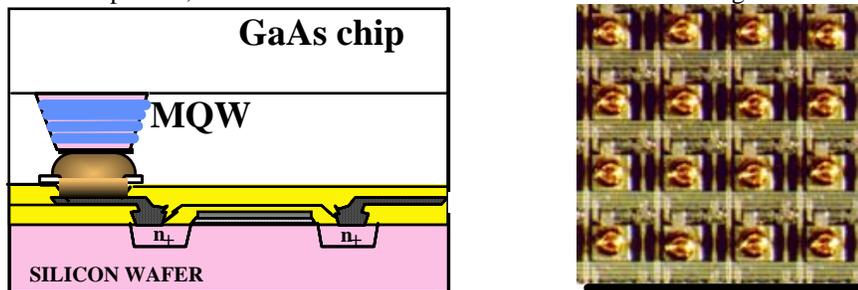


Figure 1: Cross-sectional view of a Smart Pixel and a silicon chip with gold bumps prior to flip chip bonding to an array of MQW modulator array chip.⁷

Figure 1 illustrates a cross-section of a pixel in a hybrid silicon/MQW Smart Pixel. The GaAs wafer is used to support the MQW modulators, and is transparent to the optical wavelength ($1.06\mu\text{m}$) used by the InAlGaAs/InGaAs MQW structure.¹⁰ The modulator is used in a reflective configuration and is connected electrically to the output of the silicon circuit using flip-chip bump bonding. For increased robustness, an epoxy is often used between the flip-chip bonded chips. For shorter wavelengths the GaAs substrate is removed after the flip-chip bonding process.

The flip chip bonding process sequence starts first with the preparation of the two chips to be bonded. This may involve depositing metallic films with a particular metallurgy to allow for bump bonding, and may also include fabrication or positioning of the bonds, and cutting of the chips. This step is critical to assure good bonding yield. The next step is to P&P the GaAs chip onto the silicon substrate. This step is labor intensive and generally governs the cost of the approach. The alignment tolerance which can be

achieved determines the range of applications that can be addressed with the flip-chip HI technique. Most flip-chip bonding approaches use self alignment made possible by the surface tension generated by the molten bump. This technique allows alignment tolerances approaching 10% of the bump size.

The size of the bump is governed by the bump material (e.g., gold, indium, solder or silver), and the desired distance between chips. Bumps can be made as small as 2-3 μm in diameter and can be as dense as a few million bumps/ cm^2 . When the bump size is kept above 10 to 15 μm , the flip chip process has an excellent yield and can lead to practical manufacturable chips at acceptable costs. The dimensions of the host chip is in general less than a few centimeter on the side.

Although at first, flip-chip bonding may appear an inelegant brute force HI technique, it has many features which enable it to dominate the manufacturing of hybrid devices. These features include:

- applicability to a large spectrum of devices and materials
- testability of both of the mother and host substrates prior to bonding
- well developed repeatable metallurgical process base
- well developed P&P (flip-chip aligner bonder) equipment base
- little degradation of device performance during P&P and bonding
- robust and high yield bonds

Because of these important attributes, flip-chip bonding is today routinely and successfully employed in manufacturing. However it suffers from two limitations. First, inevitably, the flip chip bump introduces a parasitic capacitance which, for some applications, such as fast light detection may unacceptably dominate receiver circuit performance. Second, the P&P ability of flip-chip bonding is limited in that it can only handle chips which are at least several hundred microns on a side. More importantly, flip-chip bonding in its present form is suitable for joining a few large chips with a host substrate, but falls far short of providing a means by which individual and incompatible devices may be efficiently integrated. Many applications including large size displays, emissive color goggle displays, smart pixels, WDM transmitter / receiver arrays and photonic bandgap structures not to mention non-optoelectronic applications including RF circuits could benefit from a more flexible P&P technology which could handle many small structures simultaneously over very large host substrates. To be effective however, any P&P technology must be fully compatible with other HI process steps including the removal of the devices from their mother substrate and the grafting of these devices to a host substrate. Before introducing a new P&P method, it is therefore necessary to first review existing processes that relate to these key HI steps.

2.2. Processes for Structure Removal from Mother Substrates

2.2.1. Epitaxial Liftoff

The Epitaxial LiftOff (ELO) technology¹¹ developed by Yablonovitch and co-workers in the late 1980's is an important technique in which epitaxial thin films are separated from their original growth substrates. This process is based on the remarkable difference (seven order of magnitudes) in the etch rates of AlAs over GaAs when exposed to buffered HF etchants. If an epitaxial film of GaAs is grown on top of an AlAs sacrificial layer, then when this structure is exposed to the buffered HF etchant solution (in liquid or gaseous form), the AlAs is dissolved, allowing the upper epitaxial layers to float away from the substrate. The process can be carried out with bare epitaxial films as well as films hosting integrated circuits or individual devices.

The thickness of the sacrificial AlAs layer is typically between 100 and 2000 Å. An epilayer designed for the implementation of a circuit is grown above the AlAs layer. The circuit is then fabricated using standard microfabrication techniques. Next, a thin film of black wax or polyimide is applied to the surface of the epilayer, to protect the fabricated circuits during the liftoff process. The black wax layer can also serve as an intermediate substrate used during the transfer process, although more rigid intermediate substrates can also be attached if desired, using the black wax as a bonding layer between the intermediate substrate and the epilayer. After curing the black wax, the edges of the epitaxial layer are exposed and the epilayer is immersed in HF acid. The AlAs layer is attacked by the HF acid, and the edges of the epilayer film are lifted up by the tension induced by the black wax. This epilayer curvature aids the etching process by allowing the reaction products to diffuse away from the AlAs layer. Eventually, the AlAs is fully dissolved, and the epitaxial layer floats away from the GaAs substrate. If post-ELO processing of the epitaxial layer is needed, a high melting-temperature wax can be used during the liftoff procedure. The high melting temperature of the wax allows such processes as metal evaporation to be performed on the lifted off epitaxial layers, following their removal from their mother substrate.

ELO is a powerful technique for removing fabricated structures ranging from sub-micron devices to as large as 4" wafers from their mother substrates. It has now matured to the point where it has been generalized for usage with other materials and etchants. Figure 2 shows an SEM picture of GaAs islands transferred onto sapphire by ELO. In this sample, photoresist was used for bonding the GaAs islands on sapphire. ELO has been primarily used together with direct bonding methods to transfer a variety of devices, device arrays, and circuits from their mother substrates onto silicon CMOS circuits.¹²⁻¹⁹

We should note that initial work on the ELO of VCSEL's encountered difficulties in protecting the high aluminum concentration in the VCSEL mirror layers while removing the sacrificial AlAs layer. In addition, VCSEL performance degradation seen in lifted-off VCSEL's was attributed to strain effects during the bending of the epilayer during ELO²⁰. To resolve these types of limitations, many researchers prefer to separate the structures of interest from their mother substrate by substrate removal.

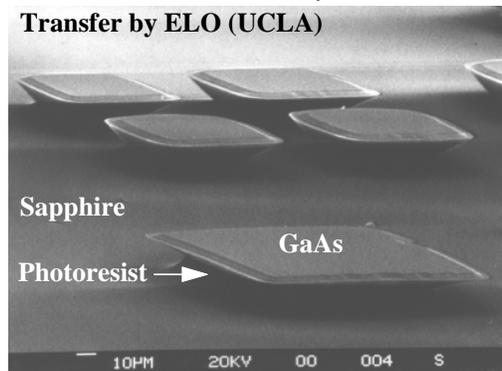


Figure 2: An SEM picture of GaAs Islands transferred on Sapphire using ELO.

(Courtesy of E. Yablonovitch (UCLA))

2.2.2. Substrate Removal

Techniques for substrate removal have been used since the very early days of the semiconductor industry in an effort to reduce parasitic capacitances introduced into IC

circuits by the substrates, as well as to produce support diaphragms for transmission electron microscopy. In most cases substrate removal involves a sequence of several process steps. Following device fabrication, the mother substrate is mounted face down on a superstrate. Then, using mechanical lapping techniques, the mother substrate is reduced down to a few tens of microns. This process is followed by chemical etching to remove the remaining part of the mother substrate.

One problem encountered in the substrate removal process is that the front and back sides of a given substrate are rarely, if ever, perfectly parallel. The mechanical lapping process, which removes the substrate, is also not a perfectly uniform process, and compounds this problem by making the two sides of the substrate even less parallel. Such non-parallel surfaces make it difficult to remove the structures of interest in a uniform manner. To combat this difficulty, one or more etch stop layers are introduced prior the growth of the epilayer on the mother substrate. These etch stop layers can be obtained by heavy doping (e.g., p+ doped silicon can be used as an etch stop for an n-type silicon substrate) or by introducing a different material as an etch stop which exhibits a much slower etching rate with respect to the substrate for a given etchant. For example, for $\text{NH}_4\text{OH}:\text{H}_2\text{O}_2$ with a pH value of 8.4, the selectivity of GaAs over AlAs is approximately 30:1. For example, if an AlAs etch stop layer lies directly beneath the substrate, a selective GaAs etch may be performed to remove this tilt. The thinner portions of the GaAs wafer will be etched away first, but since AlAs is largely unaffected by the chemical etching the thicker portions of the GaAs substrate have a chance to “catch up”, and reduce any tilt introduced by the mechanical lapping process. The AlAs etch stop layer can then be removed using HCl.

InP substrates can be removed in a similar fashion by utilizing a 3HCl: 1 H₂O solution (or 3HCl:1H₃PO₄) which selectively etches InP, but does not attack InGaAs, which can be used as an etch stop layer, and subsequently be removed by 1H₂SO₄:8H₂O₂:8H₂O or other solutions. More recent studies have shown that jet etching of the substrate may be preferable to regular chemical etching for achieving better uniformity. Even when jet etching is used, however, the need for etch-stop layers remains. Indeed, for applications requiring large area substrate removal a single thin etch stop layer is often not sufficient to correct for the tilt. Thus more recent substrate removal techniques use several alternating layers of etch stop and substrate materials. Such stacks are known as smoothing layers.

2.3. Processes for Bonding and Contact Formation

2.3.1. Bump Bonding

Bump bonding process is conventionally used together with flip-chip bonding. It can also be used with substrate removal, ELO and even DNA assisted Micro assembly techniques. Metallurgical solder joints and thermocompression ball bonding²¹ using foreexample Au balls are most commonly used. These processes start with the wafer bumping process, where metal bumps are formed on aluminum pads. To this end, many techniques can be used including e-beam evaporation followed by a lithography step and electroless plating. Once the bumps are positioned on one of the chips (or sometimes on both chips) and the chips are flipped and aligned with each other, they are pressed against each other in the presence of heat. The bump strength is important for the mechanical integrity and overall reliability of the interconnect. Critical parameters include thermode temperature, base temperature, bonding pressure, and bonding duration. Many different bump materials ranging from solder bumps to gold balls are being used.

2.3.2. Direct bonding

Once the thin-films are separated from their mother substrates they can be direct-bonded (DB) to foreign substrates, if the bonding surfaces of the epilayer and the host substrate are sufficiently smooth. In such cases, no adhesive is necessary. The bonding forces result from Van der Waals bonds between the epilayer and substrate molecules.

2.3.3. Formation of Ohmic Contact by Metallurgical Bonding

An even more attractive bonding method to achieve good thermal and electrical contact can be achieved through the annealing of a gold or palladium-coated epilayer and substrate.^{22,23} In particular, the use of an e-beam deposited Pd-Ge-In-Sn contact metal in this annealing process leads to the accumulation of Ge at the GaAs interface through diffusion processes. This produces a self-aligned Ge layer with the GaAs substrate, and results in a high quality ohmic contact. Excellent mechanical and electrical contact characteristics can easily be achieved with this method.²⁴⁻²⁶ In a similar way the use in eutectic proportions of Au and Sn can lead to strong mechanical and low resistance contacts.²⁷

2.3.4. Adhesive Bonding²⁸

When electrical ohmic contact is not critical, and thermal conductivity requirements are not stringent, bonding can also be carried out through the use of epoxy and conductive adhesives. This leads to practical low cost solutions when bonding area surfaces are rough or when structures of interest need to be bonded top-down. The electronics assembly industry has rediscovered conductive adhesives which are Pb-free as a replacement for solder based joining materials. These intrinsically clean bonding agents are often used for their favorable environmental attributes. However, new polymer solders also allow low temperature processing, finer pitch assembly and wider process latitude while providing compatibility with a much larger range of materials than solder. State-of-the-art adhesives are oxide-tolerant and no fluxing or cleaning is required.

Z-axis or anisotropic bonding agents are unidirectional conductive materials that solve fine pitch interconnect problems in several areas. The anisotropics now dominate the flat panel interconnect field. Z-axis adhesives are also beginning to enable high density multilayer circuits and MCMs to be built more effectively. Finally, Z-axis offers the simplest and most cost-effective means for flip chip bonding. However, special equipment is required.

2.3.5. Wafer Bonding

Direct wafer bonding technology has recently attracted significant attention and industrial acceptance because, unlike other material joining techniques, it can yield a robust, atomically smooth, electrically conductive, and optically transparent bonding interface with very simple apparatus. Recently, tremendous progress has been made in both the fundamental understanding of the process²⁹⁻³⁶ and its optoelectronic device applications³⁷. Today, the direct wafer bonding technology has been developed into a manufacturing process suitable for mass production.

A typical wafer bonding process consist of three steps, including surface preparation, placement of the substrates in contact with each other, and temperature annealing while the substrates are maintained in high pressure contact. The surface preparation step is critical to remove oxides and organic contaminants, as well as for the chemical activation of the surfaces for interfacial bonding.³⁸ Bonding by Van der Waals forces occurs when two such clean surfaces are brought together. Chemical bonding and re-crystallization takes place during the elevated temperature anneal which follows. The annealing is

carried out in a conventional furnace in H₂ ambient. As an example, InP and GaAs can be bonded together by ramping the temperature from room temperature to 555 °C in 30 minutes and maintaining the temperature at 555 °C for 30 minutes before naturally cooling down the system. The pressure during bonding is in the range of 1 to 20 MPascal. For III-V/Si bonding, more than 600°C temperatures are required at higher pressures.

Wafer bonding leads to a covalently bonded heterointerfaces and epitaxial layers which are free of threading dislocations. Thus, by employing the direct wafer bonding technology in an unconventional way, one can form a highly compliant substrate on which defect-free heteroepitaxial layers can be grown with what would conventionally be unacceptably large lattice mismatch to the substrate.^{37,39,40} This new capability may have a tremendous impact on microelectronic and optoelectronic industries by bringing two incompatible materials together.

2.4. Processes for Pick and Place

2.4.1. Robotic Precision Pick and Place

Today the manufacturing of electronic PCB boards as well as multi-chip modules is carried out with powerful Pick and Place machines equipped with advanced robotic features including vision systems capable of distinguishing between several types of components. These machines are fast and achieve respectable positioning accuracy (~50µm) over more than 50cm PCB boards. However, their operation remain mostly sequential, in that components are placed serially. Also, the components which can be assembled in this fashion are limited in size to larger than a few millimeter. Several attempts are being made to apply this type of P&P approach to handling micron size devices. Most approaches rely on using a micromanipulator under a scanning electron microscope or atomic force microscope. Indeed micrometer-size particles can be picked up and placed with a needle-shaped handling tool⁴¹ because adhesion forces due to electrostatic forces and Van der Waals' forces can be made to dominate the dynamics of the micro-objects. To control the pick-and-place activity of the micro objects, the tool trajectory and the material combination must be carefully taken into account. Although excellent alignment accuracy can be achieved, the operation of this type of tools is however, serial and very slow.

2.4.2. Manual Alignment

When devices do not need to be handled individually and are held together with an intermediate substrate or the mother substrate, Flip-chip aligner bonders¹ are used. This type of equipment is now widely available at reasonable costs with a few micron alignment resolution over a few centimeters. In addition, with the advent of self-alignment procedures relying on the surface tension of the molten bumps, finer alignments are possible down to 10% of the bump dimensions. However, flip-chip aligners are limited to handling devices larger than ~ 1mm, and must operate sequentially.

One of the attractive features of ELO epitaxial layers handled with a transparent intermediate substrate such as a polyimide diaphragm, is the ability to use a mask aligner to align the lifted-off structures onto the host substrate. This technique can achieve sub-micron alignment tolerances. In addition, by complementing this approach with a probe tip to release the desired devices from the intermediate substrate, one may be able to handle small devices individually. Again, however, the approach remains serial in

nature, in contrast to the parallelism available with self assembly techniques as will be described next.

2.4.3. Fluidic Self Assembly

Fluidic self assembly has the potential to fabricate densely packed III-V devices on their GaAs substrate and then sparsely integrate the devices over a larger area host substrate such as a silicon chip.^{42, 43} In addition several different types of devices can be positioned selectively in parallel. Thus fluidic self-assembly is a new P&P paradigm enabling this function to be performed with micron size devices.

Self-Assembly is generally achieved by generating selective short range forces that are applied on randomly moving complementary parts assuring their bonding. In fluidic assembly, the forces are generated via gravity, and the selectivity is assured via geometric compatibility of the complementary parts.

Initially, the Si surface is textured with an anisotropic etch that produces 10µm deep trapezoidal holes in the surface of the Si. The III-V process begins by growing a 1.0µm etch-stop layer of AlAs on a GaAs substrate, followed by the desired epitaxial layer for device formation. The devices are then isolated by etching trapezoidal mesas. Next, the top surface is bonded to an intermediate substrate with wax and the GaAs substrate is removed. The bottom surfaces of the devices are then metallized and the devices are removed from the intermediate substrate by dissolving the wax. The devices are then suspended in an inert carrier fluid which is dispensed over the surface of the Si until the devices become trapped in the trapezoidal holes in the Si. Finally, the surface of the Si can be passivated and metallized to complete the integration with Si circuitry.

The fluidic assembly process has been used to integrate LEDs and VCSEL's with a Si substrate. This process opens a new set of capabilities in HI in offering a possible replacement for conventional P&P paradigms for micron scale assembly. However, it suffers fundamentally from several limitations that arise from its very principle. Fluidic Self Assembly only relies on weak forces resulting from gravity and on simple geometric selectivity. In nature, self assembled systems generally rely on stronger coulombic forces for bonding and on a more complex combination of charge distribution and associated geometry for selectivity.

These aspects of fluidic assembly limits its applicability in terms of scaleability, yield, and generality. We believe that the DNA assisted Micro Assembly to be discussed in the next section overcome these limitations and complements fluidic self assembly.

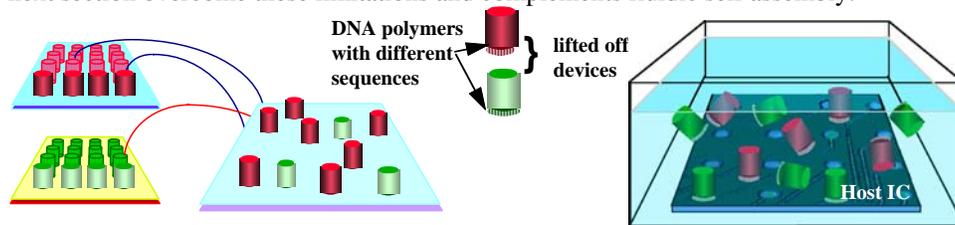


Figure 3: DNA Assisted Micro Assembly and Fluidic Self Assembly can redistribute at will, devices separated from their mother substrate onto host substrates

3. DNA Assisted Micro Assembly

DNA Assisted Micro Assembly also relies on self-assembly principles. However, in contrast to fluidic assembly, this method relies on strong coulombic forces to bring complementary parts together, it utilizes the remarkable selectivity of DNA hybridization

to P&P large numbers of different identity devices and uses strong forces that form between two complementary strands of DNA to bond the parts together.⁴⁴

3.1. DNA as a Nano Fabrication Material

Synthetic DNA polymers constitute a very promising vehicle to assemble large numbers of micro-devices, because the inherent base-pair coding property of the DNA allows specific complementary double stranded DNA structures to be formed⁴⁵. Synthetic two-stranded DNA polymers have complementary base pairs which provides an inherent self-organization mechanism. An (A)danine base on one strand will hybridize only with a (T)hymine base on the other, while a (G)uanine base has a (C)ytosine complement. Figure 4 shows the structure of the DNA molecule, illustrating the complementary nature of the base-pairing.

The complementary nature of the DNA base pairs is inherent in the hydrogen bonding properties of the base pairs, and provides a programmable recognition code which can be used for specific placement and alignment of micro-and even nano-scale devices. In the DNA-assisted micro-assembly technique, strands of DNA having, for example, the base sequence ATTTGC can be attached to a substrate in places where we want micro-devices to be attached. We shall call this DNA the “capture” DNA. The complementary sequence of TAAACG can be attached to the micro-devices. If the microdevices are now released in solution above the substrate, the capture and complementary DNA strands will naturally tend to hybridize, resulting in the automatic self-alignment and assembly of the micro-devices on the substrate at the receptor locations where the capture strands were placed. Thus, the DNA based self-assembly process relies on artificial DNA polymers as a "highly selective glue" to bring together devices with incompatible layout and structure.

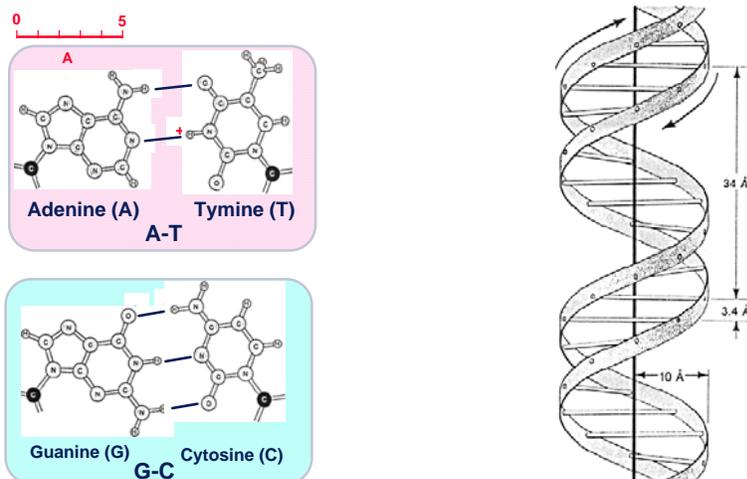


Figure 4: The DNA molecule

The DNA strands attached to the fabricated micro-devices and the complementary strands attached to the substrate allow the rapid and automatic alignment of devices to particular positions on the substrate. The approach provides for the distribution of various thin film devices onto processed silicon chips in an arbitrary fashion in one single step without any geometrical or layout restrictions imposed by the mother or host

substrates. Thus a dense array of devices fabricated on a modest dimension mother substrate can be distributed sparsely on a large host substrate. In addition because individual devices can be controlled selectively, it allows for the utilization of only "known-good-devices" with a potential to significantly improve system yields, assuming that the testing of the micro-devices can be accomplished at low cost prior to the self-assembly process.

Of course, these facts alone do not make DNA a viable nanofabrication material. In order for DNA to serve as the selective glue we have described, it must be suitable in other important practical respects. First, it should be inexpensive and easily obtainable. As it turns out, DNA polymers can be rapidly and efficiently synthesized with automated instruments at most bio. tech. companies world-wide.⁴⁶ Additionally, a number of private companies are in the business of custom designing and synthesizing inexpensive DNA sequences. The DNA strands can be synthesized in lengths ranging from 2 to 200 nucleotides (1- 60 nm) and can be synthesized with any desired base sequence, therein providing programmable recognition for an almost unlimited number of specific connections. A second requirement for utilizing DNA strands in a fabrication process is that the strands be versatile in their ability to attach to a variety of materials. Fortunately, DNA polymers can be modified at any position in their sequence, and at several places within the individual nucleotide unit itself. This provides a means of positioning functional groups, such as amines, aldehydes, and carboxyls on the DNA strands, which in turn allow the covalent bonding of fluorophores, chromophores, affinity labels, metal chelates, chemically reactive functional groups, enzymes and other biological molecules to the DNA.⁴⁷⁻⁴⁹ Additionally, DNA polymers can be both covalently and non-covalently linked to solid surfaces including glass, metals, silicon, organic polymers, and bio-polymers. Finally, DNA polymers are compatible with solvents such as acetone used in microfabrication. These practical considerations and their inherent ability to self-organize make DNA polymers attractive as a tool for HI.

3.2. Development of Key Process Steps and Preliminary Proof of Concepts

Figure 5 illustrates the sequence of a possible set of steps necessary to implement the DNA-assisted micro-assembly process. It is evident from this process flow, that the DNA-assisted micro-assembly technique requires several non-standard processing steps. Among these are:

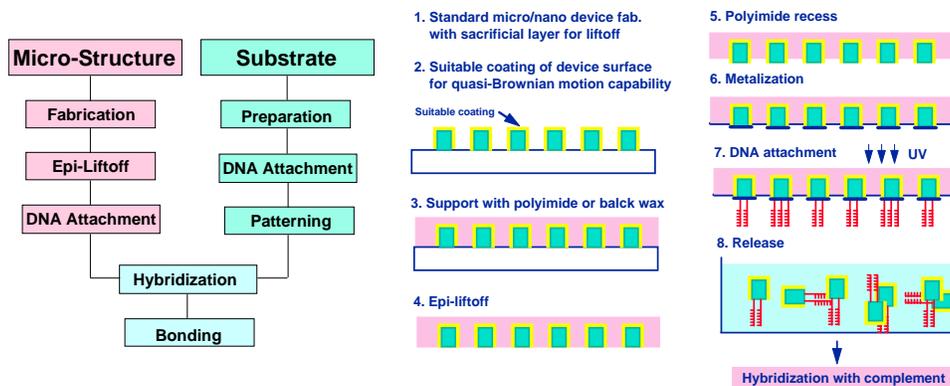


Figure 5: One possible Process flow for DNA-assisted fluidic micro-assembly of devices and substrate

- The fabrication of appropriate “capture” and “complementary” DNA strands
- The selective attachment of these DNA strands to the substrate and micro-devices, respectively
- The hybridization of capture-labeled devices with complementary-labeled substrates.

To demonstrate the feasibility of the DNA-assisted micro-assembly technique, these unconventional process steps had to be experimentally explored and proved viable. In the following we provide the details of these process steps.

3.2.1. Synthesis of Capture and Complementary DNA

We first synthesized “capture” and “complementary” DNA sequences to use in the experiments. The DNA was artificially synthesized with sequences of bases that were designed to minimize the possibility of intra-strand (self-) hybridization, while maximizing the strength of inter-strand hybridization. The artificial synthesis of DNA strands can be performed using a polymerase chain reaction (PCR) technique, which literally constructs the DNA strands from their nucleotide components. The DNA strands thus fabricated averaged 20 base-pairs (60 Å) in length. Strands of this average length were long enough to be robust, while remaining short enough to be reproduced easily. The DNA strands were synthesized to contain any of several functional chemical groups (amines, aldehydes, or thiols) at one of the ends (3' or 5') of the DNA strands. Such chemical modifications allowed a charge to be easily placed on the DNA strands, and also provided an attachment site for other biological molecules, enabling, for example, the attachment of fluorophores and polystyrene beads to the DNA strands. After synthesis, the DNA sequences were purified by high pressure liquid chromatography (HPLC).

3.2.2. Selective Attachment of DNA To Various Surfaces

3.2.2.1. *DNA Attachment and Patterning on Inorganic Materials*

DNA polymers can be both covalently and non-covalently linked to solid surfaces: glass, metals, silicon, organic polymers, and bio-polymers. These attachment chemistries are both existing and easily developed. For example, DNA sequences have been covalently attached to a number of materials which include: (i) Glass (SiO₂), (ii) Silicon (Si), (iii) Metals (Gold, Silver, Aluminum), and (iv) Langmuir-Blodgett (LB) films.⁵⁰

Glass, silicon, and aluminum structures can be prepared in the following manner. Glass and silicon (SiO₂) are first treated with dilute sodium hydroxide solution and aluminum with dilute hydrogen fluoride solution. The materials are then derivatized for covalent coupling with the attachment sequences by treatment with 3-aminopropyltriethoxy-silane (APS). This is carried out by refluxing the materials for 2-5 minutes in a 10% APS/toluene solution. After treatment with APS, the materials are washed once with toluene, then methanol, and finally dried for 1 hour at 100°C. Attachment to the APS derivatized materials is carried out by reaction with the specific dialdehyde derivatized attachment oligomers (see previous section) for 1-2 hours in 0.1 M sodium phosphate buffer (pH 7.5). The silicon surface attachment procedure is shown in Figure 6.

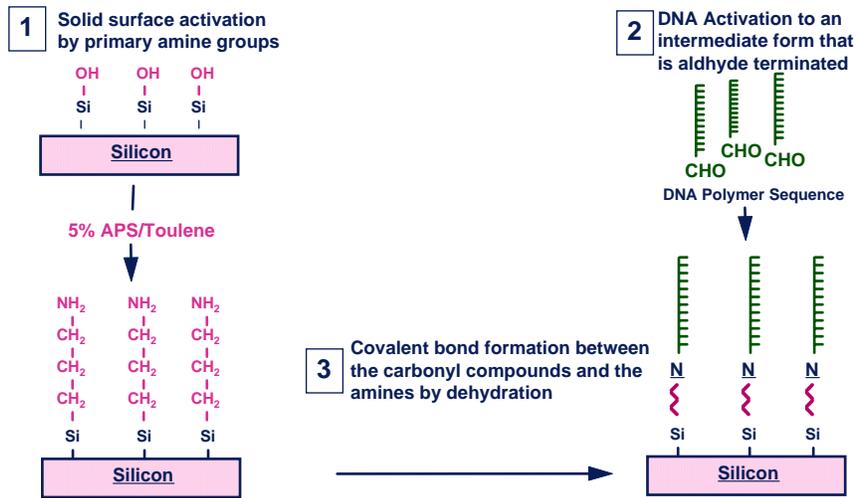


Figure 6: Procedure for attaching DNA to silicon

DNA attachment chemistry is strongly dependent upon the materials to which the DNA polymers will be attached. For example, to attach DNA to aluminum pads on a silicon chip coated with a protective glass layer, we first activate the aluminum regions by dipping the sample for a short period of time into a dilute buffered HF solution. This leaves the protective glass layer non reactive, while the exposed aluminum pads are made highly reactive to DNA. This material selectivity is a convenient and general way to attach DNA to particular regions of a multi-material substrate.

3.2.2.2. Substrate Preparation for HI of Multiple Types of Devices

The key enabling process for the robust heterogeneous integration of many types of devices on a host substrate in one fully parallel P&P operation requires the proper attachment of multiple unique DNA identities to different parts of the same substrate. The desire to place multiple DNA sequences on a substrate stems from the fact that such an ability paves the way for the parallel integration of multiple micro-devices, each coated with DNA that is complementary to one of the sequences on the substrate.

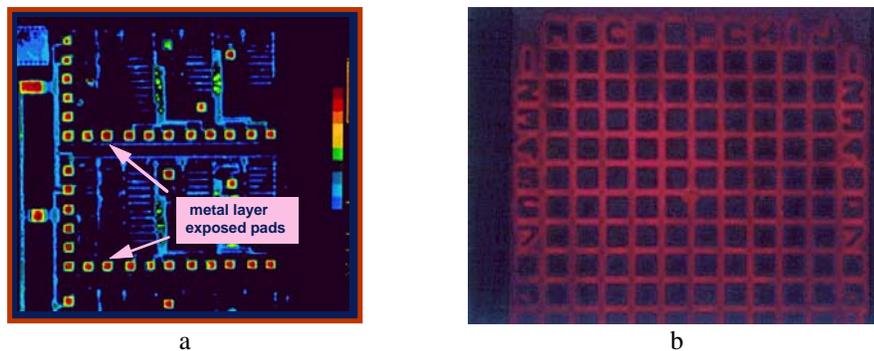


Figure 7: a) Selective attachment of fluorescent DNA sequences to aluminum pads on silicon IC. b) UV patterning of DNA on silicon/silicon dioxide/aluminum

Using electrophoretic transport, attachment of multiple DNA identities to particular locations on a substrate can be carried out sequentially. Consider the simultaneous micro-assembly of several types of specialty devices. The receptor pads need to be labeled with capture DNA according to the device to which they are to be coupled. In order to "program" a particular set of receptor pads, the appropriate capture DNA strands are released in solution above the pads. A positive bias is applied to the pads which are to be coated with the capture DNA, and a negative bias is applied to the remaining pads. The negatively charged capture DNA strands migrate, through electrophoretic transport, to the positively biased receptor pads, where they are chemically attached. This process can be repeated multiple times with different DNA strands, and different receptor pads. In this fashion, up to 60 unique DNA identities have experimentally been placed on a chip. A second method that uses a similar principle is based on optically inducing an electric field to migrate the DNA strands to desired locations.

Perhaps a more elegant approach uses a passive technique for placing multiple DNA identities on a substrate using psoralen cross-linking agents. DNA intercalated psoralen compounds when exposed to low-energy UV light (365 nm) are able to covalently cross-link DNA strands together, and this linking procedure allows the creation of multiple DNA identities on a substrate. In the first step of the process, capture DNA is attached to the substrate in a standard fashion. Let us call this DNA strand "A". Next, a second DNA strand (let us call it "B") which is "half-complementary" to the first strand is allowed to hybridize to the original capture DNA. This second DNA strand contains a psoralen molecule which, when exposed to low energy UV light, causes the two DNA strands to cross-link, effectively "gluing" them together. By selectively exposing particular areas of the chip, cross-linked strands can be formed at selected sites on the chip. The entire chip is now subjected to a dehybridization process. The DNA strands which are not cross-linked through the psoralen molecule, dissociate from one another, leaving just the original "A" DNA strand in place. The cross-linked strands, however, cannot dissociate from one another, and thus remain together during the dehybridization process. This means that the "B" DNA sequence is available for selective attachment at these locations. Two distinct DNA sequences have therefore been placed on the substrate, allowing the integration of two distinct sets of micro-devices at particular locations. If more integration is desired, the psoralen cross-linking step can be repeated with more DNA strands, ad infinitum.

3.2.3. Grafting of capture labeled Devices with Complementary Labeled Substrates

3.2.3.1. *Hybridization*

Pairs of complementary single stranded DNA molecules (disassembled state) can be reversibly hybridized into double stranded DNA helixes (assembled state) by controlling their surrounding potential energy. For example, hybridized DNA strands can be caused to dissociate from one another by heating their ambient solution above the dissociation temperature of the strands. The strands will re-hybridize when the solution is cooled. Similar effects can be achieved using an applied electric potential. The ability to selectively hybridize and dissociate DNA strand pairs is a critical property for a self-organizing materials as it allows for multiple options in the manufacture of resulting systems. DNA Assisted Micro Assembly relies on hybridization for performing the P&P operation.

Preliminary experiments illustrating the hybridization process utilized polystyrene beads in lieu of fabricated micro-devices. Polystyrene beads are readily available from several commercial sources and can be purchased in a variety of sizes, with or without a fluorescent label attached to them. Additionally, the beads can be purchased with functional groups, such as amines, aldehydes, and carboxyls attached to the outside of the beads, allowing the beads to carry a net charge, and enabling easy chemical modification of the bead surfaces. Polystyrene beads thus offer a simple and economical means by which to test the process steps of the DNA-assisted micro-assembly sequence. It should be emphasized that these beads (which can have diameters as large as 12 μm), closely resemble in physical dimensions, actual micro-devices that we wish to integrate on the substrate. It is only to avoid expensive and time-consuming device processing that preliminary experiments were conducted with commercially available polystyrene beads, instead of actual devices. Later in section 3.3, we will present results based on actual GaAs devices.

To illustrate the selective hybridization of complementary-DNA-coated micro devices with a capture-DNA-coated substrate, a SiO_2 -coated silicon chip was first prepared for use as a substrate. The preparation of the chip required that it be selectively coated with "capture" DNA strands. This was done by immersing the SiO_2 -coated silicon chip in a 10% APS/toluene solution for 2-5 minutes. After treatment with this solution, the chip was washed once with toluene, then methanol, and finally dried for 1 hour at 100°C. This APS process resulted in the formation of a dense layer of amine (NH_2) groups on the surface of the SiO_2 chip. A dense coating ($\sim 1 \times 10^6$ DNA strands/ cm^2) of aldehyde-modified "capture" DNA strands was next chemically attached to the APS-modified SiO_2 chip. The chemical attachment of the DNA to the surface of the SiO_2 -coated silicon proceeded through an imine reaction between the amine group on the APS-modified substrate, and the aldehyde group on the capture DNA strands.

Following the attachment of capture DNA to the chip, the DNA was patterned with a high energy UV write ($\lambda=255$ nm), using a conventional photolithography masking procedure. Capture DNA molecules exposed to the UV light lost their ability to hybridize with their complementary DNA strands.

The complementary DNA strands were conjugated to amine-functionalized fluorescent beads of up to 1 μm in diameter. The beads were suspended in an aqueous sodium phosphate buffer solution (pH 7.4) on the substrate, and hybridized to the unexposed capture DNA. Figure 8 shows fluorescent beads 160 nm in diameter hybridized to the patterned substrate.

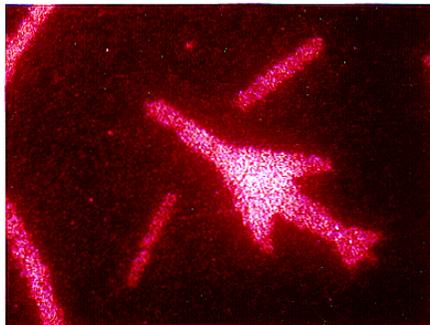


Figure 8: 160nm bead hybridized to a SiO_2 coated chip

If the devices to be aligned are numerous, and small enough to remain suspended in solution, the complementary-DNA-labeled devices can be released in solution, and simply allowed to randomly collide with the capture-labeled substrate. The probability of hybridization taking place between the device and substrate will be related directly to the probability of the proper device-host pad pairs coming into contact with each other. Since this probability distribution is expected to be random, it is imperative that the solution be saturated with devices, and that these devices be free-floating in solution, so as to prevent devices from “getting stuck” on the substrate at non-complementary positions. For beads and devices of less than 1 μm in diameter, in highly concentrated solutions, this process works reasonably well. However, when the alignment and assembly of larger devices over larger host areas is required, or when fewer devices are available for use, it is desirable to improve upon this technique by selectively causing the DNA-coated free-floating micro-devices to move towards the complementary labeled positions on the substrate in a highly directional fashion. This is of particular value with fabricated devices which are more difficult to suspend in solution than are polystyrene beads, and which are fabricated in relatively smaller number. To improve the yield further, it is also desirable to have a means by which devices can be selectively removed from the receptor pad areas if they fail to hybridize to the substrate. This eliminates “screening” effects which would otherwise prevent strong hybridization bonds from being formed between other devices. To address these issues, we use two important processes: directed electrophoretic transport, and stimulated hybridization.

3.2.3.2. *Directed Electrophoretic Transport*

The first issue, that of the directional transport of devices is quite readily achieved by exploiting the charged properties of DNA strands. The DNA strands used in the hybridization procedure can be synthesized with a net charge. If the substrate is fabricated with DNA-coated metal pads at the positions where micro-device attachment is desired, a bias can be applied to these pads which will allow the DNA-coated micro-devices, free floating in solution, to be drawn towards the substrate pads. This Coulombic attraction scheme greatly enhances the speed and reliability of the hybridization process between devices and the substrate.

To experimentally demonstrate this electric-field mediated transport, a chip was designed to serve as the substrate, which contained a 5x5 array of “capture” pads. Each of the 25 capture pads was connected by a metal line to a “contact pad” to which an electrical probe could be connected. In this fashion, each capture pad could be electrically addressed. A picture of this chip appears below in Figure 9

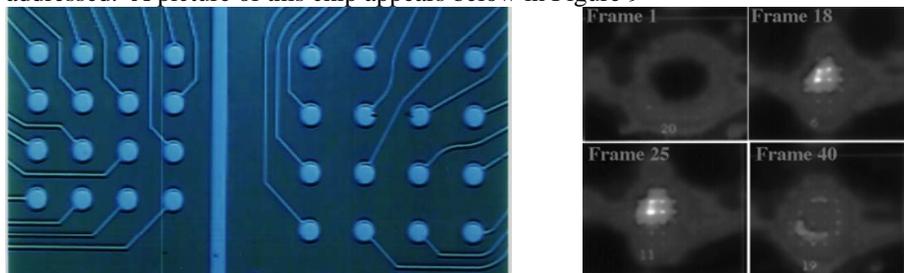


Figure 9 : a) A chip used as a substrate for preliminary bead movement experiments (Courtesy of Nanogen Inc.), and b) video frames showing movement of parts directed by electrophoresis

Fluorescent polystyrene beads which had been coated with negatively-charged surface functional groups, and having diameters of up to 10.4 μm , were placed in an aqueous sodium phosphate (pH \sim 7.4) solution. A drop of this solution was placed on the chip so that it covered the 25 capture pads, but did not touch the “contact” pads. Using a probe-card, one capture pad was biased positively, while the remaining 24 were given a negative bias. The drop of solution between the capture pads allowed electrophoresis of the charged beads in solution to occur between the contact pads, thus completing the electrical circuit. Under the influence of this electrophoresis, the charged beads selectively conglomerated around the positively-charged pad. When the positive bias was applied to a different pad, the beads migrated to this new position on the chip. A similar experiment was conducted using negatively-charged fluorescent beads up to 10.4 μm in diameter and just two active pads—one biased positively, the other negatively. Again, the beads were observed to move under the influence of the electric field, and conglomerate around the positively charged pad. It should be noted that in these bead-movement experiments, we did not coat the beads or substrate with DNA. The work previously described, involving the hybridization of DNA-coated beads up to 1 μm in diameter with a DNA-labeled substrate illustrated that we could attach devices to substrates. The bead-movement experiments described here were designed only to determine the size constraints on the micro-devices that we wish to assemble. Thus, physical attachment of the large beads to the substrate was not performed. When the bias on the substrate was removed, the beads dispersed in solution. The important aspect of these experiments, however, is that the movement of relatively large micro-devices in an aqueous solution under the influence of an applied electric field was demonstrated.

3.2.3.3. Stimulated Hybridization

The second issue involved in the hybridization process, is that of ensuring the formation of strong hybridization bonds between the substrate and devices in order to promote good alignment accuracy of the devices being grafted on the host substrate. In order to address this issue, a technique known as “stimulated hybridization” can be employed. This technique utilizes several heating and cooling cycles which are carried out during the hybridization process. During the heat cycle, weakly hybridized components are dissociated to increase the chances of the substrate forming stronger bonds with other devices. Localized AC electric fields are induced around each receptor to allow devices which fail to hybridize to the surface to be removed from the receptor pad area. This eliminates the screening effects of the unwanted devices .

3.3. An example HI Process Sequence Integrating DNA Assisted Micro Assembly for Pick and Place with Actual GaAs devices.

Having illustrated the feasibility of the non-conventional processing steps involved in the DNA-assisted micro-assembly sequence, we next began experiments using actual fabricated devices. The process sequence can be broken down into the five processing steps which we previously used to analyze other HI techniques.

Processing Step I: Device Fabrication

The first processing step is the fabrication of the microstructures. A conventional photolithography mask was designed for this fabrication. The mask consisted of four quadrants, each containing over 60,000 circles of radius 1, 2, 5, and 10 μm respectively. From this mask, “dummy devices”, were fabricated. These dummy devices consisted simply of gold contacts on top of GaAs cylinders grown upon the standard AIAs

sacrificial layer necessary for the ELO process. These “devices” had no functionality, and served only to demonstrate the feasibility of the fluidic-micro-assembly process.

Processing Step II: Substrate Preparation

The same chip, shown in Figure 9, containing the 5x5 array of capture pads that was used in the preliminary bead-movement experiments, was also used in experiments with actual devices. However in this case, it is desired to place capture DNA strands on the capture pads of the chip. DNA can be patterned directly onto the small capture pads, using a thiol-modified DNA-gold attachment chemistry. However if a bias is applied to DNA-coated metallic pads, the DNA is destroyed by the resulting electrophoresis. In order to protect the DNA on the substrate contact pads, a permeation layer is needed. To this end, on top of the chip, an agarose gel permeation layer was spun, and DNA attached to the agarose surface through a chemical attachment process. The agarose gel binds the DNA, while allowing electrophoresis to occur through the pores in the gel layer.

A problem with the agarose layer is that it is “sticky” in that DNA-coated micro-devices have a relatively high probability of sticking to the agarose layer anywhere they came into contact with it. Since the agarose-layer is spun onto the chip, it coats the surface of the chip entirely. The result is that micro-devices show a high degree of non-selective binding, sticking not only to the contact pad regions, but to the intermediate regions between the contact pads as well. This is clearly undesirable. To combat this problem, we have developed a novel procedure which allows the binding of DNA to the agarose in an acetone solution.

Processing Step III: Device Liftoff from Mother Substrate

Following the fabrication of the devices and substrate, it is necessary to remove the fabricated devices from their mother substrate. This was achieved using a standard epitaxial liftoff. The fabricated microstructures were covered with a black wax, and then lifted-off from their host substrate using an HF bath, which etched away the AIAs sacrificial layer, leaving the devices in the wax. A picture of the grown devices at this stage in the liftoff procedure is shown in Figure 10. The wax was then dissolved in TCA and the devices freed in solution. Centrifuging this TCA-device solution allowed the TCA to be removed and replaced with a sodium phosphate buffer. Following liftoff, the dummy devices were coated with DNA which was complementary to the capture DNA on the substrate.

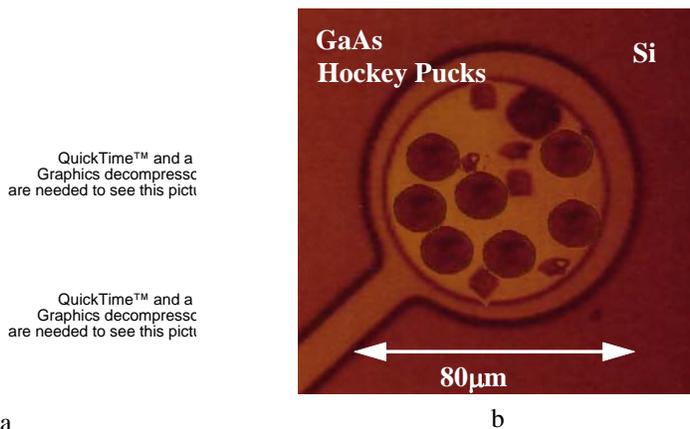


Figure 10: a) “Dummy devices”, consisting of gold on GaAs, held in a black wax during the liftoff procedure. b) Dummy GaAs devices captured on a chip pad by Coulombic forces

Processing Step IV: Device Alignment

The next processing step was the alignment of devices onto the host substrate. A drop of sodium phosphate buffer solution containing the lifted-off dummy devices was placed on the prepared chip so that it covered the 25 capture pads, but did not touch the “contact” pads. Using a probe-card, one capture pad was biased positively (3V, 1nA), while the remaining 24 were given a negative bias. The drop of solution between the capture pads allowed electrophoresis of the charged dummy devices to occur between the contact pads, thus completing the electrical circuit. Under the influence of this electrophoresis, the devices selectively conglomerated around the positively-charged pad. Figure 10b shows the dummy devices during the alignment step, being aligned to a capture pad on the substrate. The devices in this experiment had DNA coatings, but were actually not hybridized to the substrate, because the substrate in the picture did not contain the DNA complement. Thus, the devices in Figure 10b are held in place by Coulombic attraction. The important point here is that the devices can be aligned to capture pads on the substrate. The physical attachment of the devices will be a relatively simple next-step.

Processing Step V: Bonding

The DNA which holds the micro-devices to the agarose-coated substrate provides a temporary bond between the devices and the substrate. The bonds can be broken, if the chip is subjected to strenuous washing. Also, because the DNA and agarose layers lie between them, ohmic contact between the devices and metal substrate pads is not achieved. In order to form a more permanent, ohmic contact between the devices and the substrate, two options are being investigated.

In the first scheme, pressure is applied to the assembled devices, and the substrate is heated to allow a metallurgical bonding of the devices to the metal substrate. Agarose melts and DNA is dissociated at a temperature of about 80 C. Thus at metallurgical bonding temperatures, the agarose and DNA layers are destroyed, and ohmic contact is achieved between the substrate and the devices.

In the second scheme, the “host” substrate is actually a transparent medium such as quartz, or even a flexible medium such as mylar, and serves as an intermediate substrate. Unlike with ELO, the devices from different origins can now be distributed at will on this intermediate substrate. This intermediate substrate is then flipped over and aligned to the final “host” substrate. Any one of the bonding methods describe earlier can be used for mechanical and electrical contact formation. An advantage of the second scheme is that during the bonding process, no agarose or DNA is between the devices and the host substrate. Thus, it is easier to achieve ohmic contact. Also, using the second bonding scheme, pressure can be applied evenly across the intermediate substrate, allowing a more uniform bonding procedure. The two different schemes are illustrated schematically, in Figure 11 and b. These bonding procedures have not yet been fully demonstrated experimentally.

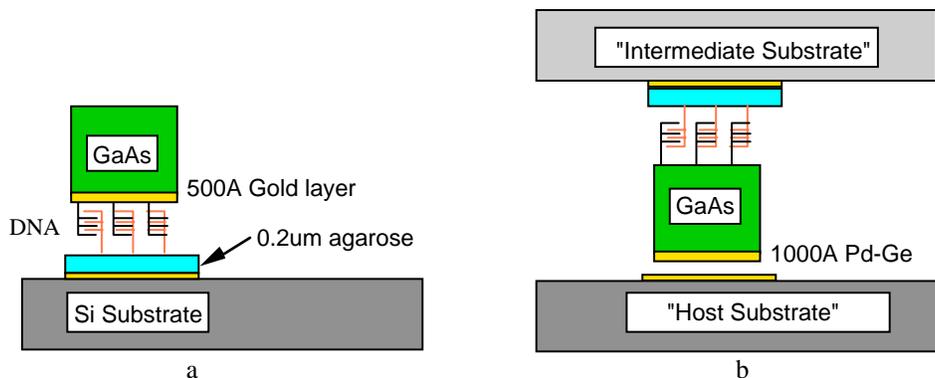


Figure 11: Two different bonding schemes for the DNA-assisted micro-assembly technique (a) Direct metallurgical bonding approach (b) intermediate substrate approach

In summary, DNA based micro-assembly relies on artificial DNA polymers as a "highly selective glue" to bring together devices with incompatible layout and structure. For this purpose, several attachment chemistries exist to deposit DNA selectively to various metallic and semiconducting materials. In addition, deposited DNA strands can and have been lithographically patterned using UV light. By binding charged particles to the DNA, or by exploiting the negative charge associated with the DNA molecule itself, DNA can and has been used to control the movements of devices from 10nm to 300µm in size under the influence of an electric field or an optical beam. Finally, patterned DNA strands deposited to a host substrate have been hybridized to complementary DNA strands attached to individual devices, bonding them in a self aligned fashion to desired locations on a host substrate.

4. Comparison of DNA-assisted micro-assembly with other Pick and Place Techniques for HI

Based on the above described processes, various HI techniques have and are being developed and by mixing and matching these processes as new applications emerge. These possibilities are schematically depicted in Figure 12 delineating presently available process sequences such as Flip Chip, ELO-DB, and Appliqué methods. A review of these process sequences can be found in reference.⁵¹

is a comparison of several important parameters involved in the P&P step of the heterogeneous integration of micro-devices. The DNA-assisted micro-assembly HI sequence has a number of advantages over other more conventional HI techniques. Of the HI sequences discussed previously, only the fluidic self-assembly technique can achieve the same sort of parallel P&P capabilities that the DNA-assisted micro assembly exhibits. ELO, Appliqué, and Hybridization HI methods are quite competitive when a few large (chip-size) components need to be integrated. However these processes become prohibitively time consuming and costly when individual devices need to be transferred one-by-one from a mother substrate to a large area host substrate.

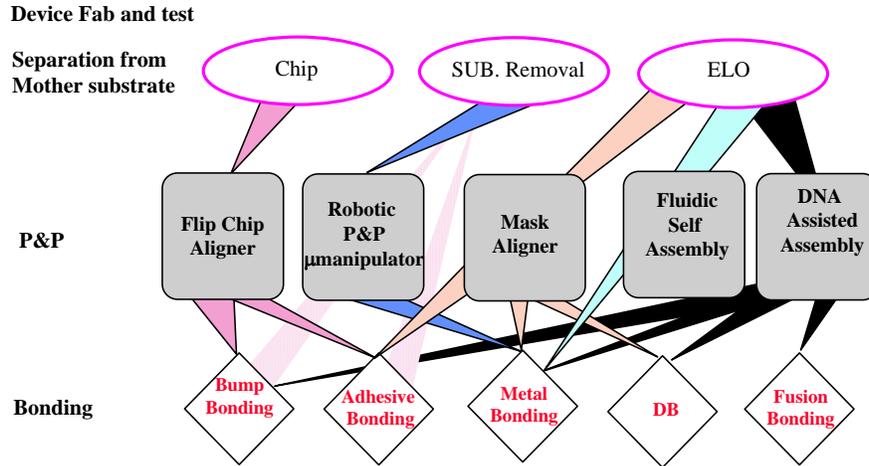


Figure 12: Summary of possible process sequences

Table 1: A Comparison of Commonly Used HI Pick and Place Steps with the DNA Assisted Micro Assembly Alignment Step

	Flip Chip	ELO with Mask aligner	ELO or Appliqué, with Probe	Fluidic Assembly	DNA-Assisted
Alignment Accuracy over Maximum Distance	~2 μ m 10% of bump Few cm	< 1 μ m ~ 6"	< 1 μ m ~ cm	Self-aligned	Self-aligned 1% device size ~ meter
Min and Max device size	> 1mm and up	> 1 mm	1 μ m and up	>5 μ m < 500 μ m	> 0.1 μ m < 500 μ m
Capability for redistribution?	No	Very slow, serial	Very slow, serial	Fast, parallel	Fast, parallel
Capability to handle multiple identity devices?	In serial with multiple flip chip alignments	In serial with multiple chip alignment	In serial with multiple P&P operations	Fast, parallel	Fast, parallel
Compatibility with bonding methods	Easy Bump Bonding	Easy Metallurgical	Moderate Metallurgical	Moderate (?)	Moderate Metallurgical / Bump Bonding
Process SpeedYield per bond?	Fast / Excellent	moderate / good	Very Slow / (?)	Fast / (?)	Fast / (?)

The fluidic self assembly technique, on the other hand, exploits a massively parallel alignment technique which eliminates the need for a laborious pick-and-place operation. For this reason, of the HI techniques discussed previously, only the fluidic self assembly technique is competitive with the DNA-based method. However the unassisted fluidic integration technique relies on geometrical properties of substrates and devices, while the

DNA-assisted micro-assembly HI technique does not. Further, the DNA assisted HI sequence can make use of the charged properties of biological molecules to direct devices to their proper locations on a substrate, while the unassisted fluidic system relies on random chance to perform the alignment. Finally, the DNA-assisted micro-assembly HI sequence provides a means by which devices are not only aligned, but also bound to the substrate, while the unassisted self-assembly technique does not. These factors give the DNA-assisted micro-assembly technique several distinct advantages over the unassisted assembly sequence.

First, the fluidic self-assembly technique relies on substrate and device geometries to perform the alignment. This means that devices, and the substrate holes into which they fit, must be tailored to particular sizes, and shapes. This effectively couples the design and processing of the fabricated devices to the alignment which follows it. Thus, a device engineer who wants to fabricate a particular device, must bare in mind the geometrical constraints and limitations imposed by the self-assembly process. This can be particularly important in the fabrication of optoelectronic devices such as VCSELs, which depend on particular cavity geometries to provide proper mode confinement. A processing sequence which requires a VCSEL to have a particular shape may limit device performance, and will almost certainly complicate the VCSEL fabrication process. The DNA-assisted micro-assembly HI sequence puts no constraints on device geometry. Micro-devices of any shape and form can be fabricated without consideration of the alignment step which follows. This decoupling of the fabrication of devices from the alignment of the devices gives device designers complete freedom in their designs.

Second, the fluidic self-assembly relies on random chance to perform the alignment of devices with the holes in the substrate. This has very important ramifications. A first-order approximation of the random-chance probability of a device aligning to a hole on a substrate is given by:

$$P = A(\text{loc}_h, \rho, \text{agitation}) * \left(\sum_x \text{OR}_x D_x H_x \right) * \left(1 - \sum_{x,y,x \neq y} D_x H_y \right)$$

where P is the probability of correct alignment, A is a constant which depends on the location of the hole on the substrate, the buoyant density of devices in solution, and the agitation provided to the solution. D and H represent the density of devices and substrate holes, respectively, summed over the number of different sets of devices (and corresponding substrate holes) that are to be integrated. The first summation term represents the probability of a given device finding it's complementary hole, and the second summation term is the probability that a given device will find the wrong hole, and block the correct match. The factor OR_x in the first summation term is the probability of a device having the correct orientation it needs to fit in a matching hole. OR_x is equal to 1 when a device set is rotationally invariant.

Even if just one kind of device is to be integrated, the DNA-assisted micro-assembly sequence can perform this task more quickly than can the unassisted fluidic self assembly technique, because the DNA assisted technique utilizes the application of an electric field to direct devices to particular locations, while the unassisted technique relies on random probability. Thus, while the unassisted technique depends on the density of holes in the substrate, there is no such corresponding parameter in the DNA-assisted micro-assembly technique. A single set of devices can be integrated roughly as fast as an electric field can transport it to the receptor pad of interest on the substrate. Additionally, the unassisted integration technique has, as part of the parameter "A" in Equation 1, some spatial dependence of the location of the substrate holes with respect to the place on the

wafer where devices are being “dropped”. Thus, a hole located in a remote location on the chip may take some time to be filled by a device, or may not be filled at all. This imposes an upper limit on the size of the host substrate for a desired yield. There is no spatial dependence in the DNA-assisted micro-assembly technique. Remote pads on the substrate may be addressed electrically, and devices brought to these pads with ease without any limitations on the size of host substrate. It should be noted that because DNA Assisted Assembly relies on the recognition properties at the molecular level, the method can provide the highest resolution and substrate sizes permitted by the lithographic processes employed.

The situation becomes bleaker still for the unassisted fluidic-assembly technique when multiple devices are to be integrated together on a single chip, or when orientation selectivity is desired. Although the fluidic-self assembly technique can use different shapes of devices to position several different devices on a wafer, and to achieve orientation selectivity, extreme care must be taken that each set of different device shapes match only one unique substrate hole, in one unique orientation. More importantly, a glance at equation 1 shows that with the inclusion of orientation selectivity, and the addition of each new type of device, the probability of a given device finding the correct spot on the substrate decreases, as the number of possible device mismatches increases. As more kinds of devices are introduced, the yield is reduced accordingly, and the process becomes prohibitively time consuming and costly. In contrast, the DNA assisted micro-assembly HI sequence, because it utilizes an electric field to draw particular devices to particular substrate locations, and because it does not rely on geometrical considerations, shows absolutely no change in the probability of alignment as the number of different devices is increased. Using the DNA-assisted micro-assembly HI sequence, many different devices can be integrated simultaneously on a wafer. Different DNA strands can be selectively attached to different positions on a substrate, and their complements can be attached to different sets of micro-devices. Moreover, each of the complementary-DNA-coated sets of micro-devices can be given a unique charge through proper attachment of a charged biological functional group to the DNA.

Suppose we wish to integrate two unique sets of devices on the same chip. One set of devices can be attached to positively charged DNA strands, and the second set can be coupled to negatively charged DNA strands. Both sets of devices can then be released in solution. With proper biasing of the substrate pads, each device will align and attach at unique substrate locations. Using this technique, we have already demonstrated that two unique sets of polystyrene beads (one charged positively, and one charged negatively), can be moved simultaneously to different locations on a biased substrate. For integrating more than two different kinds of devices, the process described in section 0. Orientation of spatially-variant devices requires patterning the devices and substrate pads as in fluidic self assembly or with different kinds of DNA in a spatially variant fashion.

A third strength of the DNA assisted micro-assembly HI sequence is that it can handle very small devices and is therefore directly scaleable with evolving lithographic feature sizes. On the other hand since Fluidic Self Assembly relies on geometric shapes for selectivity, these shapes must be resolved with a high degree of fidelity, limiting the minimum device size to many times the minimum lithographic feature size.

Finally, the unassisted fluidic-assembly sequence suffers from the fact that the overall yield is not as good as one would like. Although the technique is very successful in aligning devices to holes, the devices are often “dragged out” of their holes again by the surface tension of the evaporating fluidic solution. DNA, in contrast, provides a temporary bond between the devices and substrate, before the final metal-fusion bond is

made. Thus, the DNA assisted micro-assembly HI sequence does not suffer from the effects of the evaporating solution, and has the potential to produce commercially viable device yields.

There are, of course, many remaining issues with the DNA assisted micro-assembly HI sequence which need to be addressed. As mentioned earlier, one of the more pathological problems that we encountered during our experimentation was the difficulty of non-selective binding (NSB). As beads, or devices were made larger in size, Van der Waals bonds became more and more important, resulting in the devices “sticking” to places on the substrate, where no DNA existed. This was especially true of the “sticky” substrates, such as the agarose gel. This non-selective binding must be substantially reduced, if not eliminated entirely, if practical integration of devices is to be realized.

Several methods are being investigated to reduce the NSB in the DNA micro-assembly process. First, the NSB may be prevented before it occurs. The substrate can be mounted upside-down over the DNA solution, and an electric field used to bring charged beads (or devices) up to the desired locations on the substrate. Because under gravitational forces the devices sink in the solution, they will only come into contact with the substrate at the locations where the electric field is applied. NSB may also be prevented by utilizing the hydrophobic and hydrophilic properties of various materials to “select” particular regions of the substrate for device attachment⁵² or by roughening the surface of the substrate in those places where attachment is not desired⁵³⁻⁵⁵

A second means of controlling the NSB is to eliminate it after it has occurred. This can be done by increasing the stringency of the wash used after devices have been placed on the substrate. Increasing the stringency of the wash requires that the desired bonding hold the devices to the substrate with increased strength. Several methods of increasing the strength of the desired bonds include smoothing the substrate where devices are desired (to increase Van der Waals forces in these regions), and fabricating stronger, longer DNA strands. Utilizing some, or all of these techniques, we believe it will be possible to greatly reduce, and even eliminate NSB.

5. Applications and Conclusions

In summary, DNA Assisted Micro Assembly as a P&P technique has the following important features:

- Unequaled large placement latitude providing sub-micron resolution over distances in the order of a meter or more (in principle)
- Capability of handling nanoscale to a few hundred micrometer parts
- Capability for free distribution of parts in parallel
- Capability to handle multiple identity parts in parallel
- Good compatibility with ELO, substrate removal, bonding, and microfabrication processes (UV patterning, resistance to organic solvents
- Low cost manufacturability of key ingredients

Based on these unique characteristics, DNA Assisted Micro Assembly can be applied to widely different P&P applications as summarized below:

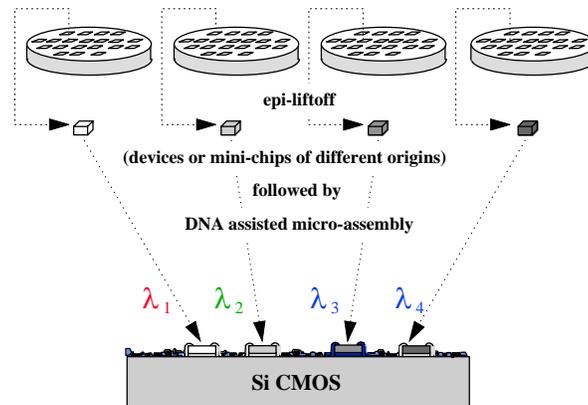


Figure 13: Integration of transmitters of different wavelength and origins onto Silicon chips by P&P

- P&P of very small components over small distances:**
 DNA assisted self-assembly can be used to cluster together on arbitrary host substrates and around arbitrary devices in an orderly fashion nano-scale device structures leading to the synthesis of 2-d and/or 3-d photonic crystals,⁵² distribution of bumps of different metallurgical properties on desired locations, formation of micro bridges and micro electrical interconnect components, self-organized masking materials for nanofabrication,⁵⁶ as well as various types of storage media.
- P&P of small components over chips:**
 In this case applications include integration of smart pixels, WDM transmitter receiver arrays (see Figure 13), emissive color retinal displays, P&P of RF and Micro Mechanical components.
- P&P of very small chips over large substrates:**
 Applications include highly heterogeneous multi chip modules with very small chips (<500 μm on the side).
- P&P of various size parts over very large substrates:**
 Applications include very large size displays including coating with various phosphor materials, or transistors for flat panel displays.

We believe that at this early stage of research, there are clear indications that DNA Assisted Micro Assembly has the potential to have a major impact on microelectronic and optoelectronic industries by bringing many incompatible materials and/or devices together.

Acknowledgments

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