Abstract
We describe technologies which can be developed to produce large area, low cost pixelated tracking detectors. These utilize wafer-scale 3D electronics and sensor technologies currently being developed in industry. This can result in fully active sensor/readout chip tiles which can be assembled into large area arrays with good yield and minimal dead area. The ability to connect though the bulk of the device can also provide better electrical performance and lower mass.

1 Introduction

In the next generation of collider experiments detectors will be challenged by unprecedented luminosity and data volumes. We will need to build large area arrays (100’s of meter$^2$) of highly pixelated detectors with minimal dead area and at reasonable cost. Current fine pitch bump bonding technologies require individual placement of chips on sensors followed by a solder melt cycle. Technologies which provide wafer-scale interconnect offer prospects of lower cost, finer pitch and lower mass interconnects between sensors and readout chips. In addition 3D interconnect technology allows connections through the bulk of the silicon, providing low inductance and capacitance paths for signal and power connections. Table 1 summarizes current and projected costs and yields of various bonding technologies.

In the past pixel sensor arrays have been limited in the module area by:

1. Space needed at the edges of the detectors to reduce the field near the damaged dicing cut regions. These regions act as charge emitters and can cause unacceptably large currents in the edge strips.

2. Die size of the Readout Integrated Circuit (ROIC), determined by the die yield and reticule area

3. The need to provide edge locations for wire bonds for connection to the ROIC.

The development of active edge sensors by C. Kenney, S. Parker and collaborators has addressed the first problem [1] [2] [3]. Recent work on the large area FEI4 chip [4] has shown that a large pixel chip
can be produced with good yield. Processes related to 3D electronics can solve the third problem. The combination of all three can result in a wafer scale fabrication of tiles or arrays which can be integrated into large modules with high yield and relatively low cost. Using such tiles, large area pixelated modules can be assembled with known good integrated sensor/readout die with large pitch backside bump bond interconnects.

Table 1: Current and projected costs and yields for sensor/readout integration technologies.

| Component                  | Current or projected cost | Yield    | Comment                                                                 |
|---------------------------|---------------------------|----------|-------------------------------------------------------------------------|
| Readout IC                | $8/cm² [5]                | 65-70% [6] | Current 3D wafer cost and FEI4 prototype yield                          |
| Active Edge Sensors       | $53/cm²                   | ≈90%     | Current cost for prototype 150 mm wafers                                |
| Silicon Strip Sensors     | $10/cm²                   | ≈100%    | CMS tracker costs                                                       |
| Bump bonding (2007)       | $213/cm²                  | 98% [7]  | CMS forward pixel costs                                                 |
| Bump bonding (2012)       | $62/cm²                   | -        | CMS forward pixel upgrade                                               |
| Wafer scale DBI bonding   | $0.04/cm²                 | ≈90%     | Projected by Yole Development [8] for high volume production            |
| Target Costs (2020s)      | $10/cm²                   | 80%      | Assuming 200 mm sensor wafers and batch active edge process             |

2 Technologies

2.1 3D Circuits

3D circuitry (3DIC) is the generic term for a set of technologies, including wafer bonding, thinning, and interconnect, which allows vertical interconnection of multiple layers of CMOS electronics [9][11]. 3D interconnects have the advantage of reducing inductance and capacitance while increasing circuit density and allowing the integration of heterogeneous device types. The key enabling technology is the Through-Silicon-Via (TSV), a metal-filled hole etched into the wafer bulk silicon which forms the conducting path between tiers of a multi-layer assembly. In high energy physics 3D circuitry would allow us to directly integrate sensors and their readout electronics without the use of expensive and cumbersome fine pitch bump bonds.

We have explored three technologies for 3D devices. Our initial studies were with MIT-Lincoln Labs and used their 0.18 micron three-tier process. This process utilizes oxide bonding to join the tiers and vias are etched through the SOI buried oxide after the tiers are bonded. We developed a demonstration 3-tier ILC vertex chip (VIP) in the MIT-LL process [11]. We have used the Ziptronix oxide bonding process with imbedded metal to mate BTeV FPiX ROIC wafers to sensors fabricated at MIT-Lincoln Labs [12]. Fermilab has also sponsored a two-tier 0.13 micron CMOS 3D IC run with Tezzaron/Global Foundries [13][14] that features 1.2 μ diameter, 6μ deep tungsten filled TSVs. In this process wafers were bonded face-to-face utilizing either copper thermocompression or the Ziptronix Direct Bond Interconnect (DBI) oxide bonding process described below. Bond pitch for these wafers was 4 microns. After bonding the top wafer is thinned to expose the tungsten through-silicon-vias and the top is patterned to provide contacts for bonding. The final set of wafers from Tezzaron have been received. The copper-copper wafers suffered from alignment...
problems, lowering the yield of good chips, but the DBI wafers have both good alignment and yield.

Other 3D processes are becoming commercially available. IBM and Micron Semiconductor will soon announce a 3D stacked memory product based on IBM’s 32 nm TSV process [15] with copper stud bonding shown in figure [1]. This technology is based on die-to-die bonding, potentially maximizing yield by utilizing known good die from both sensors and ROICS. Combining this process with active edge sensors could provide a very appealing path toward active tiles which could be used to build large area sensors. CEA-LETI is offering ”Open 3D” services for prototyping and/or low volume production. Via-last processes, such as provided by LETI, can provide TSVs in processed wafers, with the limitation that the wafers must be thick enough to handle (≥100 microns) and the TSV aspect ratio is generally limited to less than 20:1.

![Figure 1: Cross section of a 3D assembly utilizing the IBM 32 nm copper stud 3D interconnect process.](image)

### 2.2 Active Edge Sensors

Active edge sensors are an outgrowth of work done to develop 3D sensors, which provide good charge collection combined with radiation hardness. The technique utilizes a deep reactive ion etch of silicon to create a nearly vertical trench with smooth edges. The high quality of the trench wall avoids charge generation normally associated with saw-cut edges and allow closer placement of adjacent sensors. The trenches are filled with doped polycrystalline silicon. The dopant is diffused into the surrounding single crystal silicon and annealed for activation. The dopant density gradient will make an electric field in the collection direction. These steps may be done at the same time for the other like-type electrodes. The depth of the doped silicon must be great enough so it is not depleted by the largest applied bias voltage. Mechanical integrity is maintained by bonding the sensor to a support wafer. The oxide bond also forms an etch stop for the trenching and singulation processes. In the case of an oxide bonded handle, in a silicon-on-insulator structure, the bond also forms an etch stop for subsequent trenching and singulation processes. An alternative active edge technology based on wafer cleaving and atomic layer deposition [16] has the prospect of achieving similar goals without the additional processing needed in the deep trench process.

### 2.3 Oxide Bonding

Bonding of silicon wafers is a key enabling technology for nanotechnology, micromachining, and 3D electronics. A variety of techniques have been developed, including adhesive bonding, metal eutectic bonding, and bonding based on the silicon oxide surface either grown or deposited on a wafer [17]. Oxide bonding has the advantages of being mechanically robust, chemically inert, and capable of withstanding the high temperatures typical of silicon processing.

The direct oxide bond [18] is formed by bringing together silicon wafers which have been planarized
and chemically treated to form a hydrophilic surface. When the wafers are brought together at room
temperature a van der Walls bond forms between the hydrogen atoms at the wafer surface. Further
annealing above 150°C causes the formation of covalent hydrogen bonds and provides a substantial increase
in bond strength. The Ziptronix DBI process imbeds nickel or copper in the planarized oxide surface. The
metal forms an interconnect to a seed metal layer in the resulting oxide bonded wafers which can be used
to build 3D interconnect structures [19]. The process requires good planarity, which is a feature of modern
CMOS processes. Dust particles present during the bonding process can produce local bond voids. These
unbonded areas limit the large area module yield and are a motivation for active tile development. The
DBI process can be used for wafer-to-wafer or chip-to-wafer bonding. However the wafer to wafer process
is least expensive and most well suited to scaling to large volumes.

2.4 Interconnect

Once bonded to a sensor, connections need to be made to the ROIC, which is now face down. Normally
in a bump bonded pixel detector assembly the chip area is larger than that of the sensor with bond pads
extending out of the edges. In an oxide bonded assembly signals as well as power need to be brought in
through the bulk silicon of the ROIC. If the ROIC has imbedded through silicon vias the wafers can be
thinned and vias exposed using the same technique utilized in the Tezzaron two-tier 3D integrated circuit
run. A non-TSV wafer can be used by thinning the top silicon to \(\approx 10\mu\), etching that silicon to the I/O pad
contacts, and depositing a redistribution metal layer to provide the final contacts through what normally
would be the bottom of the ROIC. The redistribution layer can provide interconnects between adjacent
chips, route power, and bump bond pads. This layer can also provide ”stitching” between adjacent reticules
to provide a large effective area which can be defined at the dicing stage.

An alternate interconnect approach is to utilize so-called 2.5D interconnect. This technology utilizes a
silicon or glass interposer which incorporates TSVs and redistribution of signals (figure 2). This approach
decouples the 3D processing from the sensors and readout chips and offers a substrate with very fine
interconnect capability and coefficient of thermal expansion match to the silicon ROICs and sensors.
An interposer-based solution could partially decouple sensor and ROIC pitches, allowing for a variety of
external interconnects, and allow for conventional bump bonding of ROICS.
3 Large Area Assembly

We now consider techniques for the fabrication of large area arrays utilizing the tools described in section 2. All are based on wafer-to-wafer bonding of sensors and ROICs utilizing the DBI process.

![Diagram of wafer stack and DBI bonding process](image)

Figure 3: Top - 3D sketch showing a view of the wafer stack, including handle wafer, trenches, and the region between reticules. Bottom- Schematic view of the final stack with DBI contact layers and sensor and top contacts.

3.1 Tiles with Active Edge Sensors

We are currently exploring a process which utilizes "standard" active edge sensors. These are n-on-p devices with 200 micron thick sensors in an SOI stack with a 500 micron thick handle wafer. The tiles are fabricated by DBI bonding the sensor wafer stack to a dummy ROIC which rearranges the signal contact pattern. After bonding contacts on the dummy ROIC wafer are exposed by grinding and etching away the dummy wafer silicon substrate and first layer of oxide to expose what would normally be the bottom surface of the readout pads. This surface is then metalized to provide sites for bump bond placement. The stack is shown in figure 3. Finally the active die must be singulated. This is accomplished by etching the 10 microns of dummy wafer silicon and 3 microns of oxide, followed by an etch of the 200 microns of polysilicon filling the trench. The SOI oxide forms an etch stop in this process. The wafer is then attached to a temporary handle wafer and the original SOI handle is ground away, leaving isolated tiles.
3.2 Post-Processed Tiles

A simpler variant on the above process would DBI bond ROIC and untrenched sensor wafers. The tiles are then defined by etching trenches in the backside of the sensor wafer. The etching process is low temperature and should not harm the ROIC. However the resulting edges would not have the doping that normally defines the side electrode in active edge devices. Post-trench doping and annealing would not be possible, since the anneal would require higher temperatures than could be tolerated by the ROIC. In this case a process similar to that explored for slim-edge fabrication, utilizing atomic layer deposition to activate the edges should provide acceptable performance. This process avoids the SOI stack needed for the initial sensor wafer, provides a more planar surface for oxide bonding, and avoids the complex singulation and handle wafer removal necessary with the pre-processed active edge devices.

This process is very similar to plasma dicing, which utilizes the same deep reactive ion etching process to dice wafers [20], so it should be commercially available for both 200 mm and 300 mm diameter wafers.

3.3 Die-to-Die tiles

An alternative which utilizes the die-to-die capability of an IBM-style process could bond active edge sensor tiles to ROICs with imbedded TSVs. This probably would not require ROIC and sensor wafers of equal diameter assuming the copper bond preparation process was available for the smaller diameter sensor wafers. Although this process might not have the economies of scale of a wafer level process, improved yields by utilizing tested die might make this process competitive in cost.

3.4 Interposer-based Array

If the density of voids in the DBI bonded assembly is sufficiently small an appealing assembly would utilize a silicon interposer DBI bonded to the sensor wafer. Such an assembly could, in principle, utilize the largest sensor that can be inscribed in the wafer with good yield, typically about 1 cm inset from the wafer edge. The interposers redistributes the signals to ROIC bump bonds on the top of the interposer. This works well in a situation where the area of the ROIC is smaller that that of the associated pixels.

4 Prospects

The ability to build large areas of pixelated arrays with complex readout electronics will be crucial to future detectors. Bonding costs and yield will define the limitations of these detectors. We have described a plan to demonstrate pixelated tiles or large area arrays that have the prospect of making such large area devices affordable. To complete this development sensor wafers which match the 8” diameter of the ROIC wafers are needed. Such wafers have been demonstrated in the SOI process by both Lapis/OK [21] and American Semiconductor. We expect that commercial manufacturers will soon establish 8” high resistivity sensor production.

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