Single Die 'Hands-Free' Layer-by-Layer Mechanical Deprocessing for Failure Analysis or Reverse Engineering

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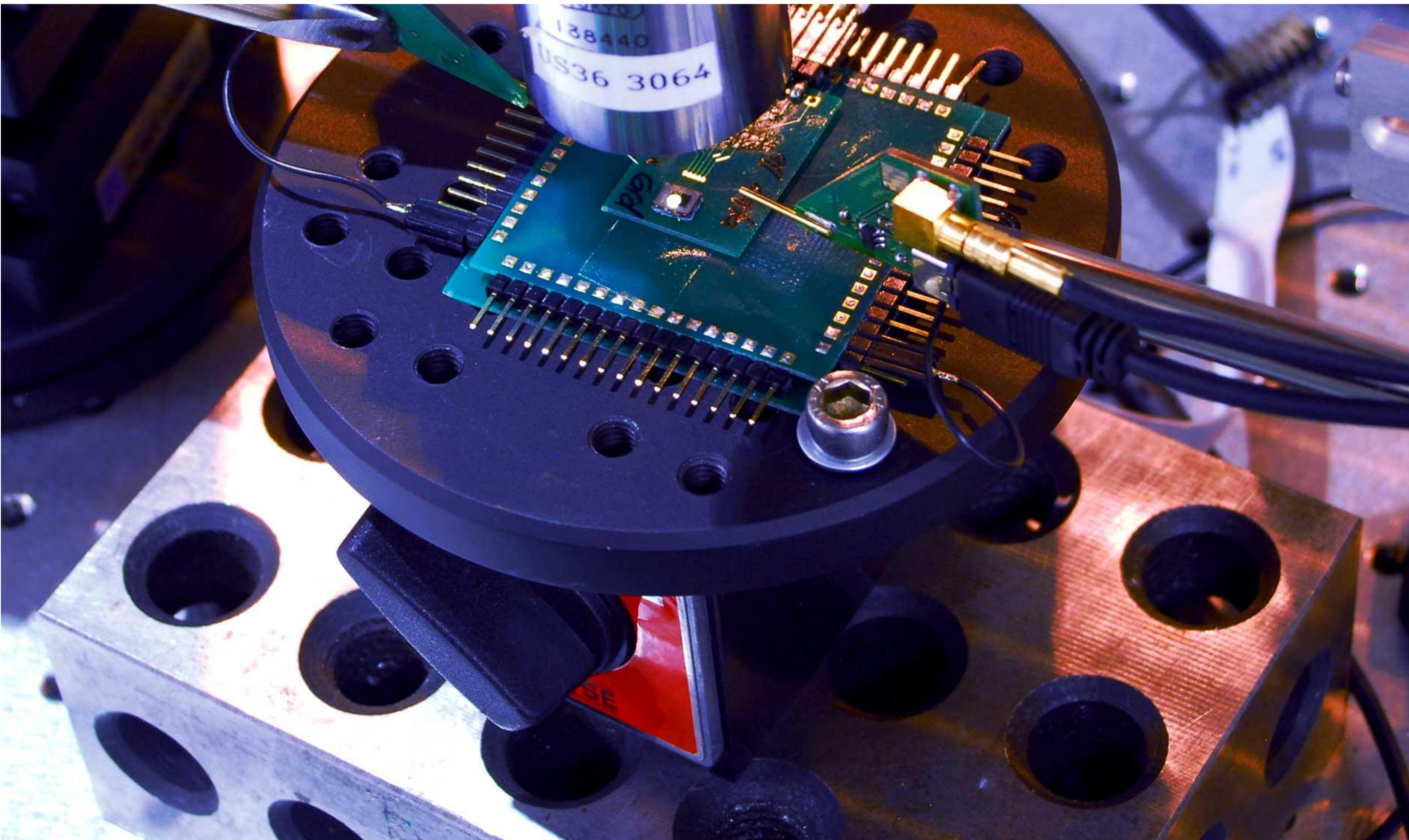

Single Die 'Hands-Free' Layer-by-Layer Mechanical Deprocessing for Failure Analysis or Reverse Engineering

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Introduction

The area of Destructive Semiconductor Reverse Engineering is a growing one and serves some very important purposes. The idea is to investigate a device in part or as a whole using many of the techniques employed in the Physical Failure Analysis (PFA) field. The device is usually examined for one of two main reasons:

- Intellectual property/patent protection
- Competitive analysis purposes

In other words, manufacturers can employ Reverse Engineering to expose any patent infringements to protect their inventions. Similarly, product developers can be users of Reverse Engineering. Understanding a device can, in many cases, be the first step in manufacturing a solution of their own. Either way, deprocessing large parts or an entire device is a routinely used and vital tool in this field.

Potential Sample Preparation Methods

Wet and dry chemical methods have for long been the most effective and reliable way of layer-by-layer deprocessing for Failure Analysis or Reverse Engineering (RE). However as technology nodes advance, new materials are introduced, and the number of layers increases, chemical deprocessing becomes an increasingly difficult task. There are many problems that are traditionally encountered when deprocessing using wet and dry chemical methods. For wet methods, these include problems like [1] the etchant attacking beyond the level it was intended to remove and also dirt/contamination issues. The requirement for the manual handling of extremely hazardous chemicals is also not an ideal situation. The main issues with dry processes are the lengthy process times and the difficulty in removing certain materials.

Figure 1 shows an SEM cross-section of a typical modern-day device. The passivation and top metal layer can quite easily be removed using wet or dry chemical processes. Once these steps have been carried out, due to the non uniformity of the metal layers, a very deep pattern in the ILD will remain. This resulting profile becomes a huge hurdle, which is extremely difficult to overcome using only chemical methods. These obstacles point the way towards a purely mechanical deprocessing method.

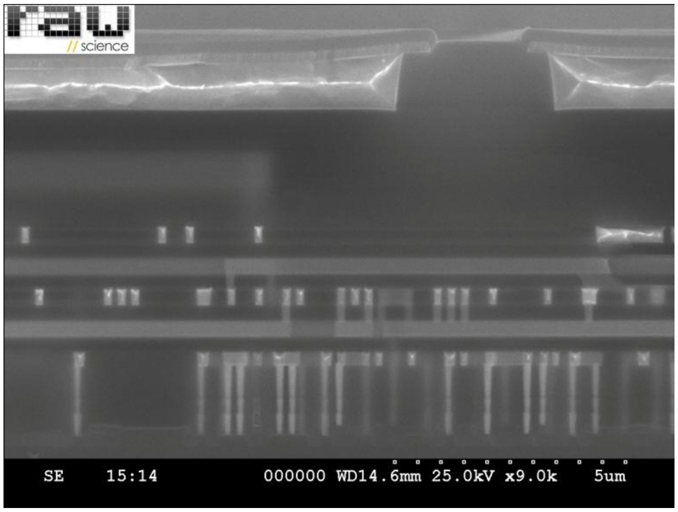

Figure 1: An x-section SEM image of a relatively modern device (7 metal layers on 90nm technology).

There are many mechanical polishers and techniques available with which an expert user can produce satisfying results. Some beveling or rounding may be evident around the edges of the resulting samples, but when an engineer has a piece of wafer to work with containing several dice, these edge effects are much less critical. The problem that is proposed is the absence of a method, which can mechanically delayer a single device with little or no edge effects so that the entire device can be exposed at the same metal or Inter Layer Dielectric (ILD) layer.

A computer controlled polishing system with an in situ optical microscope provides a number of benefits. The Gatan Frontier system controls all polishing parameters. The system allows for the adjustment of parameters such as theta and tilt angles (in 0.003° increments), speed, force, time, direction, abrasive type and brushing. The system also has continual image processing and an onboard microscope with colour CCD camera. This is incorporated into a user-friendly GUI (Graphical User Interface), which gives the user valuable feedback from the polished surface. The stitched images of the entire sample (up to 15mm x 15mm) are automatically saved to provide a polish history along with an unlimited amount of POI (point of interest) images.

The distinct advantage of using this particular system for single die mechanical deprocessing is the reliability and reproducibility, resulting in a very high sample success rate.

This paper presents a technique for the full layer-by-layer deprocessing of a single semiconductor device using purely mechanical polishing for Destructive Semiconductor Reverse Engineering (DSRE) or Failure Analysis. Although there are many mechanical polishers and techniques available in the market place which can produce satisfactory results with an

expert user, there are 2 known concerns: less than 100% success rate and edge effects which affect the overall planarity of the sample. When an FA engineer has returned parts to investigate, or more likely, when a Reverse Engineer needs to employ existing methods to investigate a device as a whole, every sample is a one of a kind and the deprocessing must be well controlled to produce 100% success. Exposing 95% of the die in the centre, leaving out edges and corners may not be good enough.

This text reveals in depth the overall process flow, conditions and preparation of the samples, which include the very important and novel changes to the standard process. These changes are required in order to delayer a single die to such a high degree of planarity, so planar in fact that 100% of the die can be exposed at the same time and at the same ILD.

Two main challenges were encountered when trying to achieve the required standard during mechanically deprocessing a single die.

Challenge 1 – Reproducibility

When preparing what could potentially be a 'one-of-a-kind' sample, it is imperative that a high degree of control is available. Manual systems which did not offer such a high degree of precise angle adjustment and controlled touchdown were therefore deemed unsuitable for this particular application.

Challenge 2 – High overall planarity

The use of conventional abrasives and methods results in unwanted edge effects especially at the leading edge of the sample. This gives an unsatisfactory result for an engineer wanting to expose the entire die at the same metal or ILD layer. **Figure 2** illustrates the phenomenon which causes the majority of the unwanted edge effects and **Figure 3** shows the kind of result typically obtained.

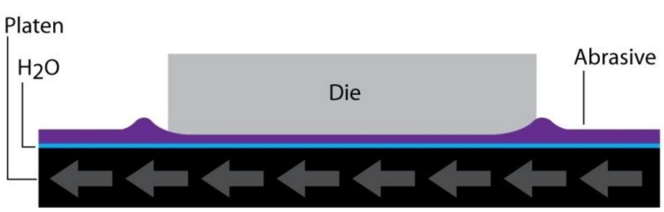

Figure 2: Illustration of how the majority of the edge effects are created.

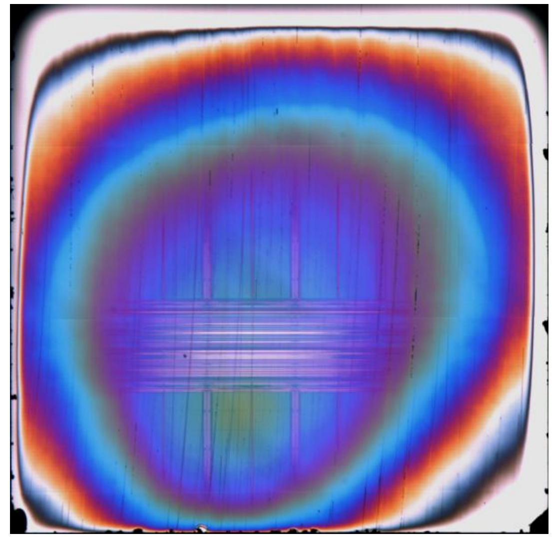

Figure 3: A typical result obtained when attempting to mechanically delayer a single die.

Herein is described a step-by-step method developed by Raw Science/Datel Design and Development and Gatan for the reliable, purely mechanical deprocessing of individual dice. The paper will present the two modifications made to the process to virtually eliminate the edge effects.

Experimental

The device used for this work was an IC based on 0.13 micron aluminium construction; it is made up of 4 metal layers and approximately 2mm squared in size. The die was supplied in a conventional TQFP44 package. The aim of the deprocessing for this evaluation was to remove all metal layers and attempt to stop at the PMD (Pre-Metal Dielectric) where we could assess both the final surface quality of the sample and also calculate the total amount of die exposed.

Stage 1 – Decapsulation

The package was decapsulated as follows:

- Hot fuming Nitric Acid (80°C) – 2 minutes
- Hot Hydrazine Hydrate (80°C) – 2 minutes
- Hot Orthophosphoric Acid (80°C) – 5 minutes

The final step in the decapsulation procedure was to [2] manually remove the bond wires using tweezers and stereomicroscope. This step is made much easier by employing the hot Orthophosphoric Acid. This weakens the bond between the pad and ball and ensures that no bonds remain on the die which could detach and cause problems during polishing.

Stage 2 – Backside polishing

The backside polishing of a die can be a very important part of the sample preparation. A planar sample back side is vital to achieving a planar front side mechanical deprocess. The sample was mounted face down on the Gatan delayering stub with clear wax of a melting point of approximately 130°C. A rough alignment for tilt and theta was carried out before polishing with a 6 micron diamond abrasive until the surface was planar. This is an especially effective step when there are residues remaining on the back side of the die from the decapsulation process.

Stage 3 – Sample mounting

The bare die was mounted on the specially designed delayering stub with the clear wax. At the leading edge of the sample, a small piece of scrap silicon (the sacrifice) slightly thicker than that of the die was also mounted. The sacrifice should be somewhere in the region of 50-100 microns thicker where possible, anything much thicker would add significant time to the process. It must also be noted that the sacrifice should overlap the die. While the stub is ~140°C, the two pieces were pressed down and together to ensure that both were flat and as close to one another as possible. The stub was then allowed to cool to room temperature.

The sacrifice is used to protect the leading edge of the sample to reduce some of the edge effects. The piece of silicon effectively takes the impact where the abrasive film deforms under the force of the sample. **Figure 4** shows the die and sacrifice on the polishing stub while **Figure 5** illustrates the results of using the sacrifice.

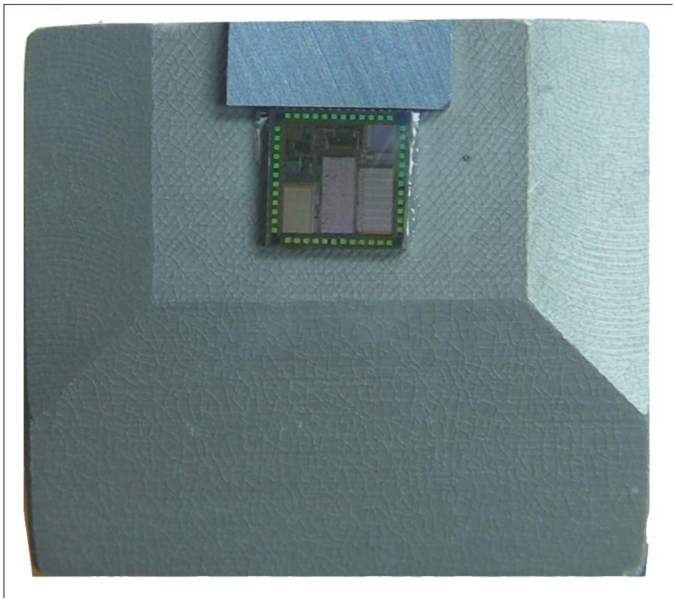

Figure 4: The Gatan delayering stub with both the sample and the sacrifice mounted and ready to polish

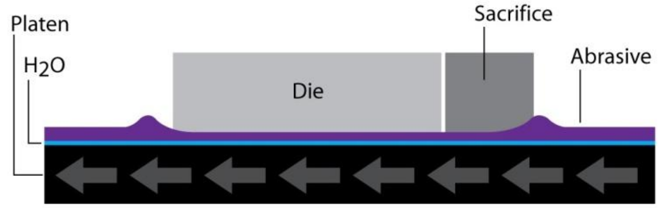

Figure 5: Illustration of how using a sacrifice protects the leading edge of the sample. The sacrifice takes the impact of the bowed abrasive instead of the die.

Stage 4 – Alignment

The sample was loaded onto the Gatan Centar Fontier and the die located on the screen. The first step in the alignment procedure is to select the top left, then bottom right of the area to be polished. In this instance we choose the outermost points on both corners including the sacrifice. The next step is to adjust the tilt and theta using only the die as reference. The final step is to select the required polish recipe. A specially formulated recipe was developed for this application and is seen in **Table 1**.

Step	Abrasive	Force	Rotation	Speed	Brushing
1	**6.00um**	**200g**	**CCW**	**100rpm**	**Full**
2	**1.00um**	**200g**	**CCW**	**60rpm**	**Full**
3	**0.50um**	**200g**	**CCW**	**60rpm**	**Full**
4	**0.10um**	**200g**	**CCW**	**60rpm**	**Full**

Table 1: The specially devised recipe used for the evaluation.

Stage 5 – Sacrifice polishing

As there is a height difference between the die and the sacrifice, the first rule in the polish recipe is to grind down the sacrifice to a height similar to that of the die. For where the sacrifice is under 100 microns thicker than the die, a diamond abrasive of 6 micron is used. Where the sacrifice is over 100 microns thicker, a coarser grade of abrasive could be used (eg. 30 micron diamond) to reduce the process time. Using the software, the exact height difference between the two pieces can be measured after each polishing increment. By carrying out an initial measurement, a rough estimate can be made as to the duration of the first polish. After the initial polishing increment, the user can re-measure and thus be more confident as to the duration of the second increment and so on. When the height difference is around 10 microns, one can say that this is close enough. Polishing any closer with a 6 micron abrasive may result in damage to the die.

At this point the surface area of the sacrifice can be reduced by 'bevelling off' some of the surplus material with the 6 micron abrasive. Carrying out this fairly quick process can reduce the polishing time significantly. With this particular system, the theta angle can be offset to a maximum of 3°. The

theta should be adjusted to negative 3.000° on the GUI and polished for a few seconds before observing the results. This can be repeated until only a thin strip of the sacrifice is parallel to the die. When there is only a small amount of material in front of the die, one can move onto the second polishing step, which employs a finer diamond abrasive and begins polishing the die itself. **Figure 6** is a stitched image from the Frontier software of the sample with the sacrifice 'bevelled-off'.

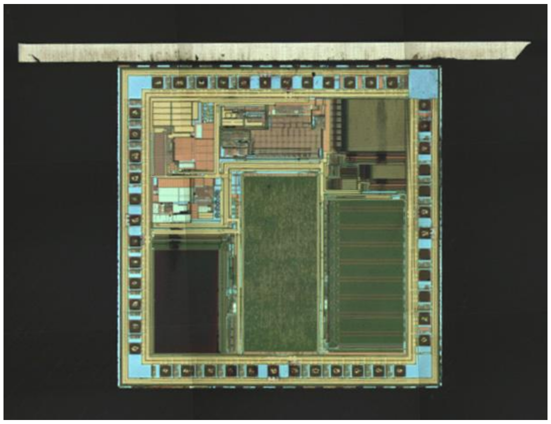

Figure 6: An image of the sample with the bevelled sacrifice. Only the very thin strip of silicon which has not been bevelled is visible.

Stage 6 – Die polishing

For the die polishing, the abrasive is changed to the finer grade (diamond, 0.5 micron in this case); an initial polish of approximately 2 seconds can be carried out. Feedback is supplied via the GUI and the user can then judge the subsequent polish times. The tilt and theta angles can be changed in 0.003° steps as the polish progresses.

It is important to note that for the die polishing, a thinner backed abrasive is used (1mil as opposed to 3mil). The use of the thinner abrasive not only reduces the amount the film deforms at the edges and corners of the sample, but also at the gap between the sacrifice and die. There are inevitably some small gaps between the die and sacrifice due to the wafer dicing process chipping off some small pieces of the die. The abrasive bulges up into the gap and creates a small but noticeable amount of overpolish at the interface of the die and sacrifice. This effect is illustrated in **Figures 7 and 8**.

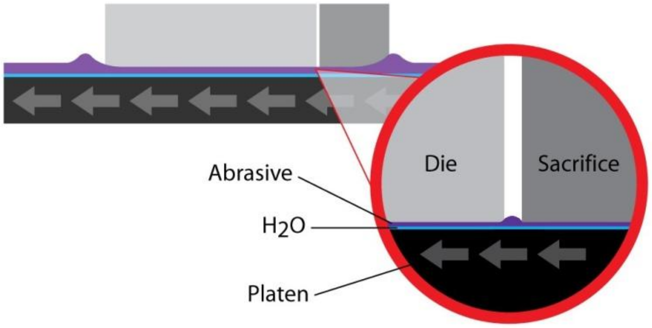

Figure 7: An illustration showing how the standard thickness abrasive bulges between the small gap between the die and sacrifice resulting in some overpolish at the leading edge.

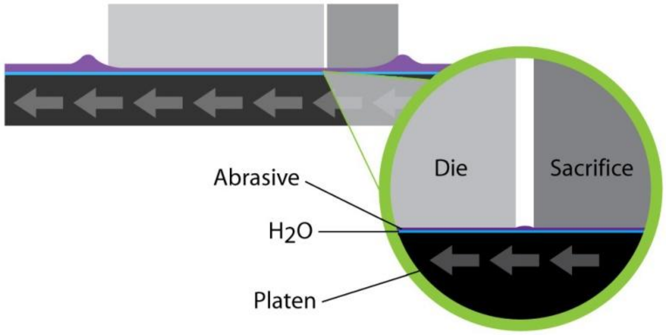

Figure 8: This illustration shows how the bulging and thus overpolish is reduced when using a thinner backed abrasive.

The 0.5 micron abrasive was used for the removal of the top two metal layers before moving onto a 0.1 micron diamond for the thinner lower metals.

This process was carried out on two further samples to be used as benchmarks. Both samples were prepared without employing a silicon sacrifice. One was prepared with a 1mil film, the other one with a standard 3mil backed abrasive. In all cases the process flow, abrasive grades and polish parameters were identical.

Results

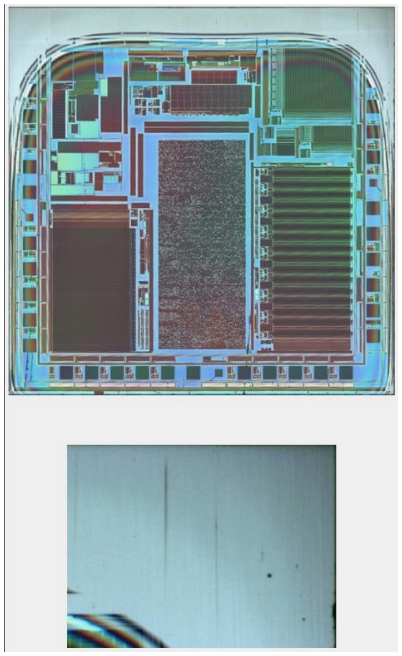

Figure 9: Standard process using 3mil backed abrasives without a sacrifice

Figure 9 shows very good results when using standard 3 mil backed abrasives without the employment of a silicon sacrifice. The edge effects are however quite apparent and some of the circuitry has been polished away. These effects are also exhibited (albeit to a much lesser extent) at the back edge of the sample.

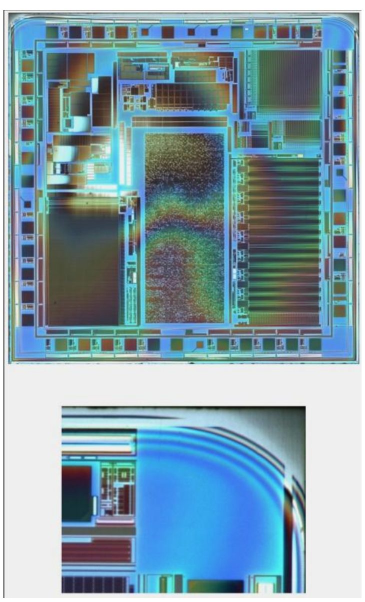

Figure 10: Modified process using 1mil backed abrasives without a sacrifice

Figure 10 shows a huge improvement by employing thinner backed 1 mil abrasives without a silicon sacrifice. There is no rounding at the back edge of the die and only a limited amount at the front. In most cases, this result would be satisfactory.

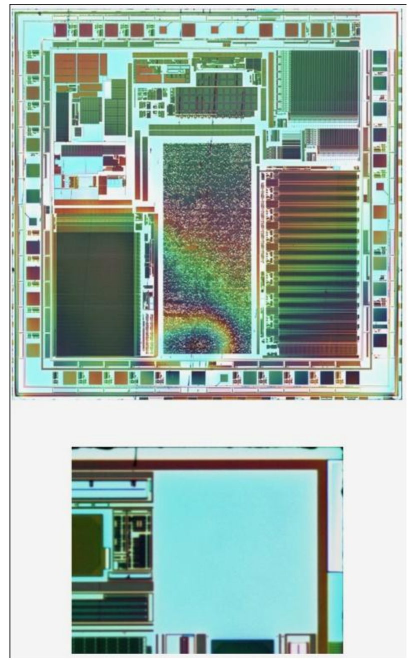

Figure 11: Final process utilizing both 1mil backed abrasives and a sacrifice

Figure 11 illustrates how all edge effects have been eliminated by using both thin backed abrasives ***and*** a silicon sacrifice at the leading edge of the die. This could be of particular use where a die has bond pads located in the centre of the die instead of the edge. In these cases, the reduction of edge effects is more crucial as the circuitry which may be of interest may be located very close to the edge of the die.

Conclusions

The area of Destructive Semiconductor Reverse Engineering (DSRE) is a growing one and serves some very important purposes, such as intellectual property/patent protection and competitive analysis. Sample preparation is critical for accurate DSRE and requires a full layer-by-layer deprocessing of a single semiconductor device.

Current techniques fall short in 2 areas:

- limited success rate
- edge effects, or ‘rounding’

A computer controlled mechanical polishing system coupled with a unique customized process allow for the investigation of those one of a kind samples as a whole with 100% success rate.

This technique could easily be applied when using any orbital polisher but when coupled with the success rate of this particular system, a unique opportunity for single die high accuracy layer-by-layer mechanical deprocessing is presented.

Although the samples all displayed a high quality finish, there was a small amount of scratching evident. This could possibly be overcome by the use of softer abrasive films such as Al_2O_3 or SiO_2 as opposed to diamond. It must be noted however that these may not be commonly available in a thinner backing.

The technique has not been properly assessed on samples of smaller geometries but this example die shows the general improvements in the process. Further enhancements could be made by placing sacrifices on all edges of the die. This has been found to have some merits when dealing with 90nm and smaller technology nodes.

Another point to note is that changing between 3 mil and 1 mil backed abrasives on the same sample proved to be very problematic. This is due to the sample creating different footprints when it is pushed down into the surface of the abrasive. The result is an uneven and difficult to control polish.

References

[1] Wills, Kendall Scott, Texas Instruments, “Planar Deprocessing Of Advanced VLSI Devices.

[2] Beck, Friedrich, Integrated Circuit Failure Analysis, Wiley, pp. 22.