Patent grouping descriptions

Patent Grouping	Details	Patent number	Territory Granted	Date granted
1	**Grinding Machine Spindle Flexibly Attached To Platform. Flexure axes, machining method.**	**GB2314037**	**UK**	**19-12-2000**
	Grinding spindle mounting Overall machine. Includes Acoustic sensing of grinding wheel contact.			
	Grinding Machine Spindle Flexibly Attached To Platform	**US6217420**	**USA**	**17-4-2001**
	Grinding Machine Spindle Flexibly Attached To Platform	**EP0907461**	**Europe**	**9-1-2002**

These patents cover many of the key features of the complete machine system.

The key features patented in the claims are:

- The use of flexures (solid steel hinges flexible in only one direction) as the pivots for grinding or polishing machine axes. Using flexures to control the machine axis motions had many advantages:
  - They are highly stiff, orders of magnitude more stiff than conventional machine axes which use either linear ball or linear air bearings.
  - They have virtually zero reversal errors. This means that when the axis is reversed, it follows virtually the same path as it took whilst advancing. This makes the machine motions highly repeatable and predictable.

    The following is an example of how this was important to SiWEG to achieve ductile regime grinding:

    As the grinding wheel finishes its cut, it obviously then has to be withdrawn from the component. With conventional linear axes, at the instant the wheel is withdrawn there is always a very slight reversal error motion as the wheel starts to follow its slightly different return path. This motion causes unwanted contact between the wheel and component and often causes damage to the component's surface. The use of flexures eliminated this error and subsequent component damage. Prior to this invention, very expensive hydrostatic or aerostatic bearings had to be used to achieve polish quality grinding.

- The combined use of flexures and spring loaded cams to drive grinding or polishing machine axes. This configuration minimizes the potential for damaging vibrations between the grinding wheel and the component by:
  - The drive mechanism is highly compact (requiring around 20% of the length of a conventional drive mechanism). Thus its critical drive and position control components can be very closely coupled to a highly stiff mount structure which can damp the damaging vibrations. Again this is not possible with conventional machine systems.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
2	**Grinding machine tight stiffness loop concept** Edge Grinding Machine. Tight and consistent stiffness Loop for wheel forming and grinding. Unwanted axis motions are constrained in directions that cause relative motion between grinding wheel and component			
	Improvements In And Relating To Grinding Machines.	**GB2322318**	**UK**	**2-11-1999**
	Grinding and Polishing Machines	**US6461228**	**USA**	**8-10-2002**

These patents cover the grinding machine's mechanical configuration the methods used to minimize the stiffness loop and maximize the damping between the grinding wheel and the component to be ground.

The stiffness loop is defined as the shortest path of interconnecting machine structure between the grinding wheel and the component. The shorter the stiffness loop the higher will be the natural frequency at which there is relative motion between the grinding wheel and component. It is this relative motion that causes damage to the component and wear of the grinding wheel.

Finite element analysis was used to design a very tight stiffness loop and the first natural frequency was calculated to be 85Hz. However at this frequency the grinding wheel and component move in unison and there is no relative motion between wheel and workpiece, thus no damage.

The first natural frequency to exhibit relative motion was 145Hz for the SiWEG machine compared with around 40Hz for a conventional wafer grinding machine.

The theoretical work carried out prior to manufacture of these machines was proven when the machines were tested.

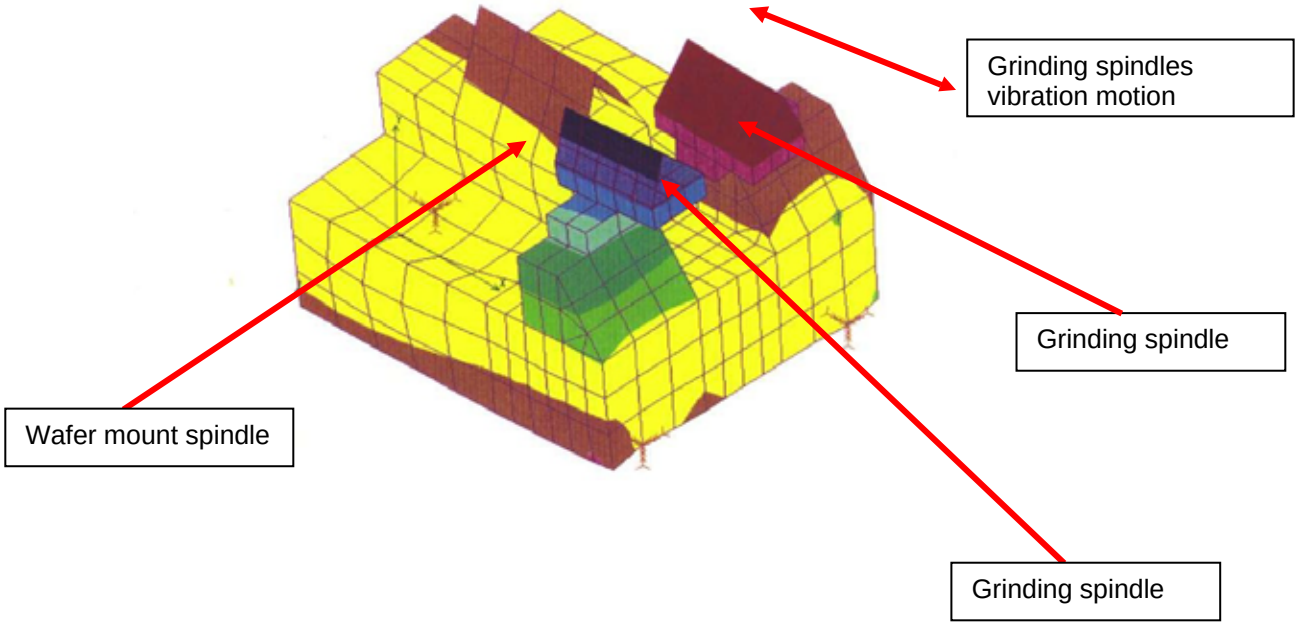
Over page there are copies of:

- Natural frequency plot of a conventional machine configuration.
  The colors represent relative displacements of the machine elements at the extremes of the vibration motion. Where the colors are the same, there is little of no relative motion between those machine elements.

- 1st natural frequency plot of the SiWEG machine.
- 2nd Natural frequency plot of the SiWEG mahcine.
- Actual measured frequency response of the SiWEG machine. There is a peak at around 83Hz, the frequency was the machine's lowest natural mode but one that was not damaging to the component. It can also be seen from the plot, that there is no spike at 145Hz. This plot demonstrates that it was relatively easy to excite the lower, frequency but extremely difficult to excite the damaging 145Hz frequency.

It was critical to the success of SiWEG that the natural frequency modes predicted be achieved. Had they not, the machine would not have produced ductile regime grinding.

Machine Design 1

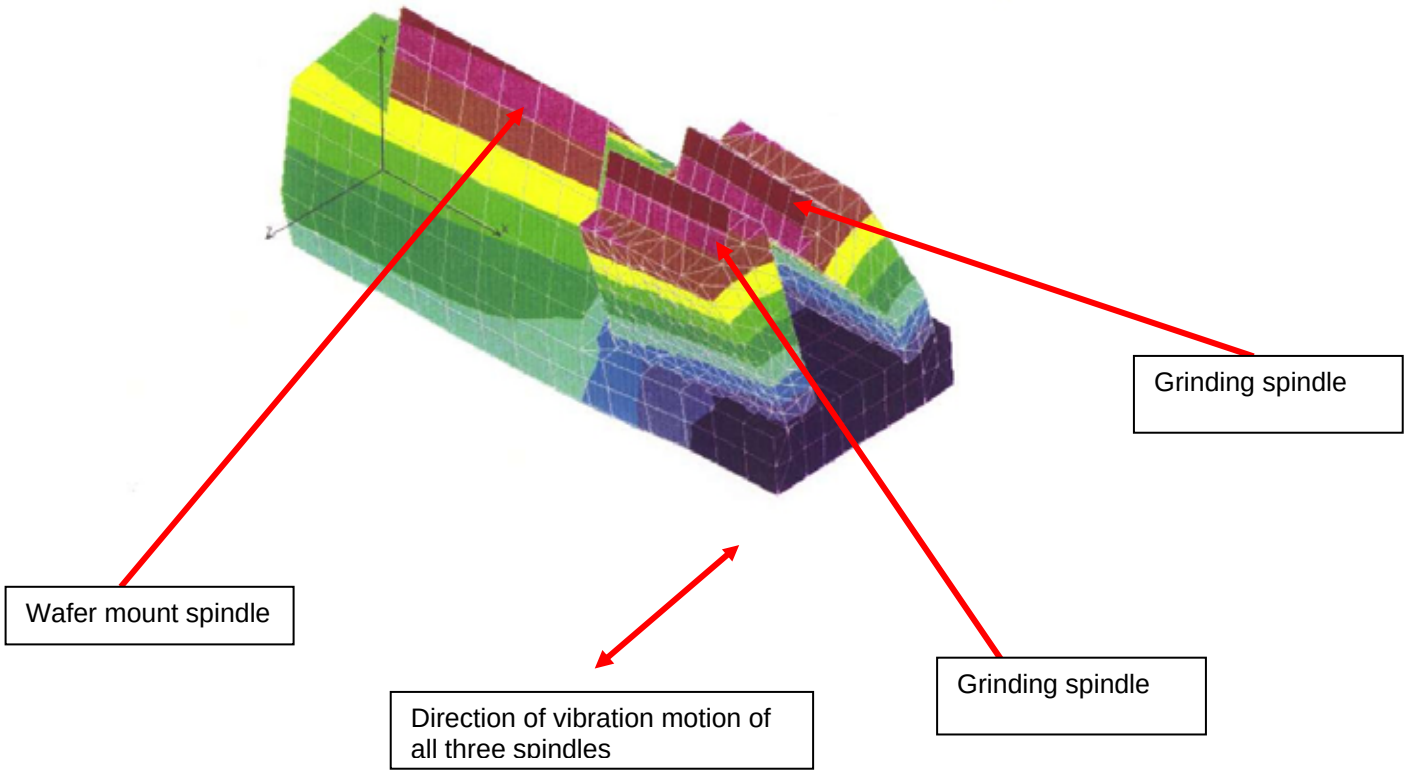


This is a finite element plot of a conventional machine.

Both grinding spindles are vibrating in the direction of the arrow above. Because the grinding wheel groove wraps around the wafer to produce the ground profile, this motion causes the sides of the grinding wheel grooves to vibrate against the wafer, which in turn caused severe wafer damage. This motion had always limited the performance of complex profile grinding machines before SiWEG.

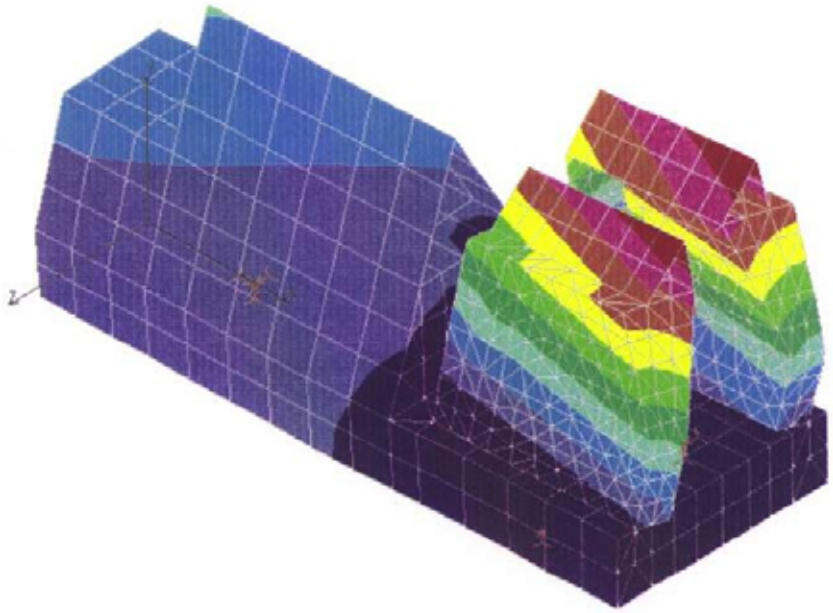
This damaging mode of vibration occurs at 40Hz.

Machine Design 2



This is the first natural frequency of the SiWEG machine. The model predicted that this would occur at 85Hz. Note that the three spindles are all red indicating that there is little or no relative motion between them. Thus there is little or no damage induced in the wafer when the machine vibrates at this natural frequency.

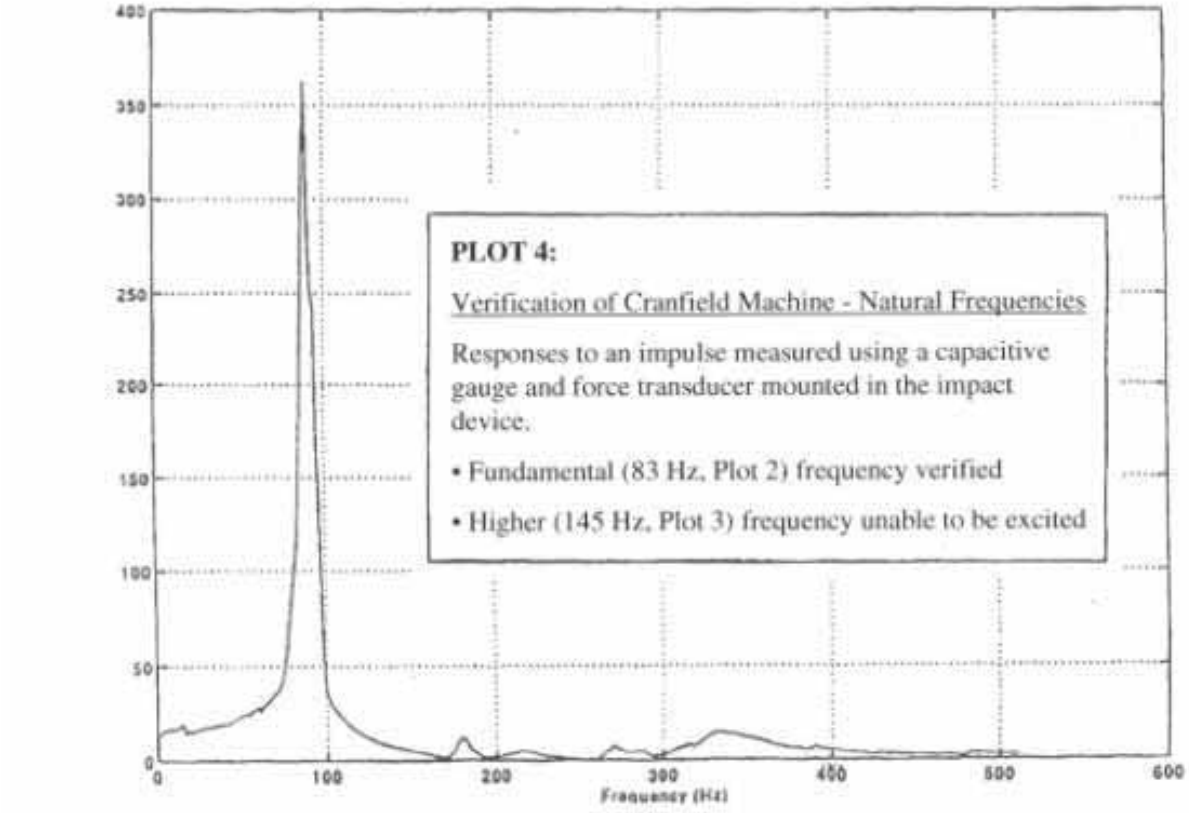
Machine Design 3



This is the first frequency which has relative motion between the grinding and wafer mount spindles. The wafer mount spindle is stationary during this vibration mode, the grinding spindles are vibrating in the direction of the arrow.

This frequency is predicted to occur at 145Hz.

Machine Design 4



This is a plot of the actual, measured frequency response of the SiWEG machine.

The correlation between the predicted (85Hz) and actual (83Hz) is clearly demonstrated as is the inability to excite the damaging 145Hz frequency.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
3	**Edge Grinding Silicon Wafer Workpieces.** Equipment patent for forming Use of metal bonded roughing wheel followed by formable CBN/Diamond wheel			
	Grinding Wheel Forming	**GB2317585**	**UK**	**2-11-1999**
	Grinding Machines and Polishing	**US6267647**	**USA**	**31-7-2001**
	Grinding Machine Spindle Flexibly Attached to Platform	**EP1005955**	**Europe**	**3-12-2002**
	Edge Grinding Silicon Wafer Workpieces. Method patent for forming			
	Edge Grinding Silicon Wafer Workpieces	**GB2322319**	**UK**	**1-12-1999**

This is one of the most significant of the SiWEG patent groups as it covers the process and equipment employed by the machine.

- The use of in-situ diamond forming wheels.
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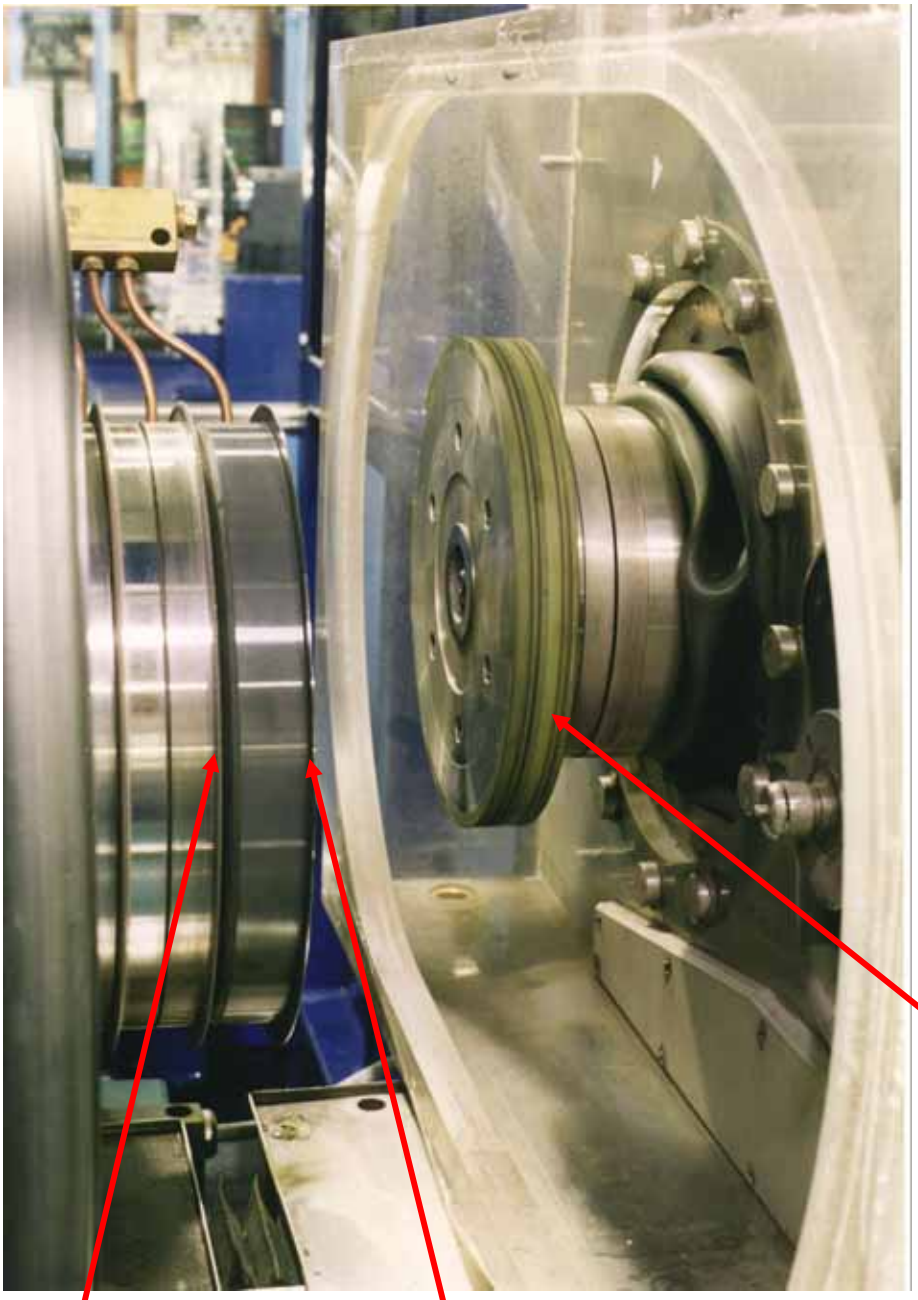
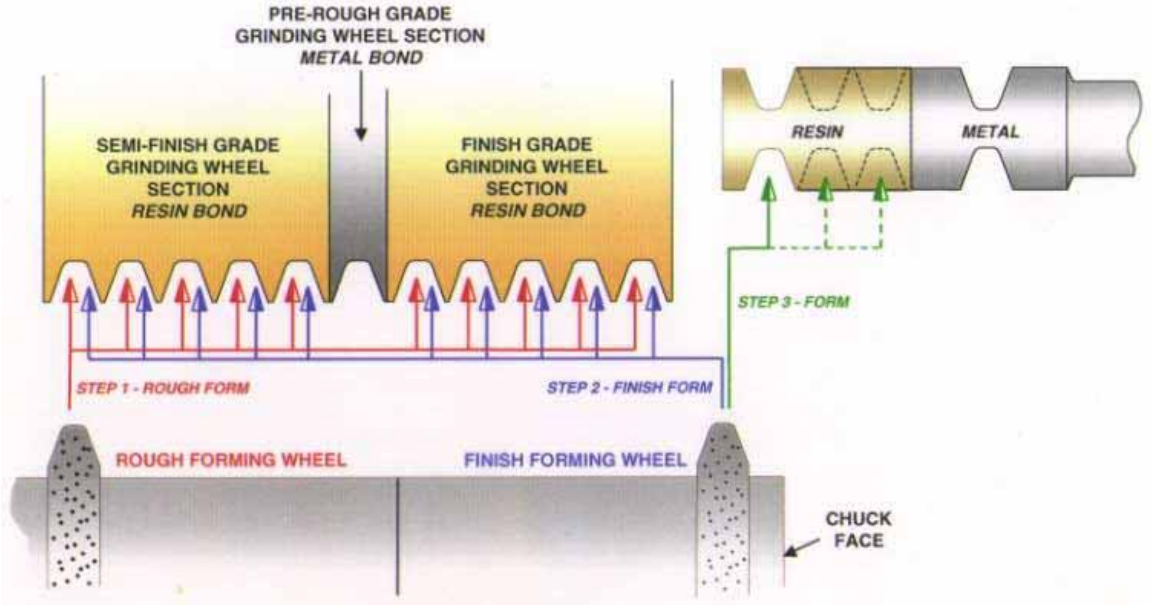
  This enabled the ductile regime grinding of complex forms for the first time. Prior to this machine's invention, ductile regime grinding using resin bonded grinding wheels had only been possible for relatively simple shapes.

- The sequential use of three edge grinding wheels all mounted upon the same spindle.
  1. A very coarse grit 'roughing' diamond in a metal bond,
  2. A coarse grit 'semi finish' Cubic Boron Nitride (CBN) in a resin bond.
  3. A fine grit 'finish' diamond in a resin bond.

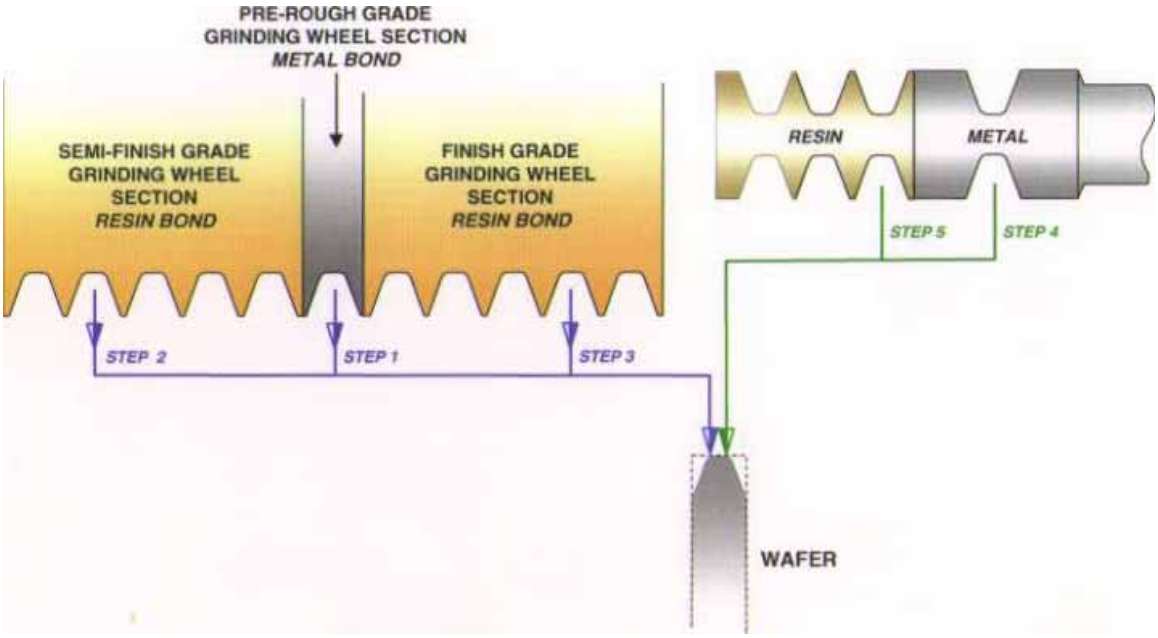
  Three grinding wheels with very different characteristics are mounted upon the same grinding spindle. Each perform a different function in the production of the ground edge finish. The metal bonded wheel is shaped by the grinding wheel manufacturer and is not re-shaped on the SiWEG machine. It has a very long life and is used to remove the bulk of the wafer edge to minimize the work for the softer resin bonded semi-finish and finish wheels. Having the two resin bond wheels mounted on the same grinding spindle enabled them both to be formed using the same forming wheel mounted on the vacuum shuck spindle. This ensured that both resin wheels had an identical form and that the machine configuration (and stiffness loop) were identical when both wheels were formed. This is critical to enabling the machine to produce near polish quality ground edges with the fine diamond grit 'finish' wheel in a production environment. Prior to this invention, the high wear rates suffered by the fine diamond wheels meant that it was not possible to produce complex profiles in such wheels and to maintain the form for any reasonable time. Thus before SiWEG, grinding complex shapes on brittle materials to this quality was not practical in anything other than research or very low volume production environments.

  The pictures over the following page show the grinding wheel and wafer spindle positions and a schematic representation of the machine's dressing and grinding procedure.


Grinding wheels
Forming wheel
Wafer



Dressing procedure



Grinding procedure.

Note that the wafer is mounted very close to the ‘finish forming wheel’ as it is mounted on the ‘chuck face’ once the forming operations are complete.

This produced a virtually identical machine stiffness loop for both the forming and grinding processes. This is a configuration that is unique to the SiWEG machine.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
4	**Workpiece inspection and Handling: plus optical inspection**			
	Workpiece Alignment and Handling system. Wafer inspection and automatic correction by handling system to locate wafer concentrically onto grinding vacuum chuck	**GB2316637**	**UK**	**22-2-2000**
	Workpiece Inspection and Handling. Camera system used inspect silicon wafer for diameter, notch location and ground edge profile	**GB2337111**	**UK**	**15-3-2000**
	Workpiece inspection and Handling	**US6224459**	**USA**	**1-5-2001**
	Workpiece inspection and Handling Including aligning wafer to eliminate damage	**EP0906174**	**Europe**	**28-8-2002**
	Grinding machine spindle flexibly attached to platform Automatic detection of grinding wheel wear and wheel reforming	**EP1005956**	**Europe**	**30-7-2003**

This is a wide ranging group of patents that contain granted claims having significance beyond the field of silicon wafer machining.

The granted claims mainly cover the combined use of a robotic wafer handling system combined with an optical inspection and calibration system.

The key features patented in the independent claims are:

- Using a custom designed CCD camera vision system to determine the shape size and position of on silicon wafers as they enter the grinding machine system. The inspection information is used to precisely align the wafer on the grinding machine vacuum chuck.
- Using the camera system to detect grinding wheel wear (by inspecting wafer edges after each has been ground).
- The use of a highly rigid and kinematically mounted space frame to link the grinding machine, inspection station and robotic handling equipment. The space frame provided a fixed and stable reference between the three key machine system elements. This enabled the SiWEG machine to carry out self checking routines to maintain positional alignments between the grinding spindle and the inspection station. Prior to this invention, this level of self checking was prohibitively expensive for use on production development machine systems.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
5	**Grinding a small section of wafer to:** • **Condition wheel** • **Measure ground section and align wheels** **Use ELID to shape forming wheels**			
	Edge grinding Combines resin wheel conditioning, grinding wheel alignment and ELID shaping of forming and grinding wheels	**US6881130**	**USA**	**19/4/2005**
	Edge grinding disc shaped workpieces Combines resin wheel conditioning, grinding wheel alignment and ELID shaping of forming and grinding wheels	**GB2351684**	**UK**	**12-6-2001**
	Improvement in and relating to edge grinding Conditioning of resin notch wheel by grinding part of a wafer edge Re-shaping forming wheels by ELID.	**EP1200228**	**Europe**	**20-4-2000**
	Improvement in Positioning Grinding Wheels Grinding small portions of the wafer's edge and measuring position for wheel alignment	**EP1260312**	**Europe**	**23-6-2004**

These SiWEG patents relate to the use of the machine's inspection system to automatically align the grinding wheel profiles to the silicon wafers. This has been a long standing problem with all grinding machines when trying to use grinding wheels which have their form machined into them before being mounted on the grinding machine.

It is critical that the form of the silicon wafer's edge be centered to the wafer by no more than 0.01mm. Most of the traditional grinding wheel alignment issues did not apply to the SiWEG machine because the finish and semi-finish grinding wheels were formed in-situ. However, to maintain the life of the softer, formable wheels a very hard wearing metal bonded wheel was used to remove the bulk of the wafer material. It is essential that the metal bonded grooves (which cannot be formed in-situ) be aligned to within 0.005mm of the formed grooves in the softer wheels. To achieve this, three small arcs are ground around the wafer's edge by the metal bond wheel. The wafer was returned to the machine's inspection station and the axial position and the diameter of the ground arcs is measured. This information was used to determine the metal bond wheel groove's diameter and axial location.

This invention enabled the machine set up time to be reduced by around an hour.

The patenting of this procedure is important as it covers the use of any grinding machine which has a profile alignment requirement and not just Cranfield's SiWEG machine.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
6	**Notch grinding wheels and processes** **Grinding Machines.** Notch grinding wheel. Resin bond or resin bond + metal bond roughing	**US6220938**	**USA**	**24-4-2001**
	Improvements in and relating to grinding machines Two stage resin bond notch grinding wheel	**GB2360965**	**UK**	**28-8-2002**
	Grinding Pin for Grinding Machines and Comprising Resin Bonded Sections of rough and Fine Grit Two stage resin bond notch wheel and forming method	**EP1251996**	**Europe**	**6-5-2004**
	Grinding Pin for Grinding Machine Two stage resin bond notch grinding wheel	**US6739954**	**USA**	**24-5-2004**

This patent covers the use of a very small (around 4mm diameter) resin bonded grinding wheel used to grind small (around 1.5mm deep) registration notches in silicon wafers. Resin bonded wheels produce a much finer grind quality and lower damage level than conventional metal bonded wheels but have a much higher wear rate. SiWEG was the first machine developed for the market that enabled on-machine forming of wheel shapes. This enabled softer, resin bond wheels to be used to grind silicon wafer edged and registration notches for the first time. The patents cover the grinding wheel design and the method of use to produce near polish quality ground surfaces in the registration notch. This technology is unique and still produces the best quality notches in the silicon wafer grinding industry.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
7	**Grinding and polishing using SiWEG**			
	Grinding and Polishing Machines Simultaneous inspection and washing of wafers in manufacturing cell	**US6095897**	**USA**	**1-8-2000**
	Wafer Edge Polishing	**GB2342060**	**UK**	**7-3-2001**
	Wafer Edge Polishing Method and Apparatus	**US6428397**	**USA**	**6-8-2002**
	Wafer Edge Polishing Method and Apparatus	**EP1089851**	**Europe**	**16-10-2002**

This covers the use of a very simple post grind polishing station which is incorporated within the SiWEG machining cell. It uses the machine system's post grind wash station to polish the wafer's edge.

Because the wafers ground on the SiWEG machine are near polish quality with very low sub-surface damage, only a very small amount of material is required to be removed to complete the polish and to guarantee that all damage is removed. With conventional wafer grinding machines these is 10-20 microns of sub-surface damage. Thus to guarantee that all of the damage is removed wafer manufacturers traditionally polished around 40-50microns from the edge. This is a very time consuming and costly process. Typically one polishing machine is required for each edge grinding machine in the production line. These machines cost $1million each. There is also around $0.5million of wafer cleaning equipment required for pre and post polish cleaning. There is an additional cost to go with each machine as they all use valuable clean room floor space which is extremely expensive to install and maintain. With the SiWEG, the sub-surface damage was only 1-2micron. Thus to guarantee that all damage was removed, only 5 micron of material needed to be removed. This meant that only one polishing machine was required for every six SiWEG grinding machine.

With such a small amount of material to be removed, it may not be necessary to use a special purpose polishing machine at all. The SiWEG grinding cell already had a post grind wash station where the wafers were to be taken and cleaned prior to post grind inspection. This station already had a motorized spindle that was used to spin the wafers dry after washing. With a very low cost (around $50000) upgrade, it was possible to incorporate a second spindle upon which was mounted a polishing wheel. Following the grind, wafers were taken to the wash/polish station to be polished and washed. This is such a rapid process that it can be completed before the inspection station became available again for the post grind inspection. Thus wafers exited the SiWEG cell having been ground and polished with no addition to the grind only cycle time.

Patent Grouping	Details	Patent number	Territory Granted	Date granted
8	**Method Of Grinding Disc (I/D O/D) Workpieces.** **Method of Grinding Disc Workpieces**	**GB2333057**	**UK**	**2-11-1999**

This patent covers the used of the SiWEG machine configuration for the grinding of computer hard drive discs.