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Authors(s)	Ahearne, Eamonn, Logan, D., Byrne, Gerald
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Dual mode control of the rotational grinding process

E. Ahearne, D. Logan, G. Byrne

The Advanced Manufacturing Science (AMS) Research Centre, School of Mechanical and Materials Engineering, University College Dublin, Dublin, Ireland

The rotational grinding process enables the production of substrates to meet the submicron planarity specifications required for micro-fabrication of semiconductor integrated circuits. Improvements in process capability, with respect to both form and finish, have been generally realised by the development of machine tools and systems based on a principle of precise and predictable "position" control. An alternative principle for optimisation is demonstrated here comprising a dual mode control system where a "finishing mode" is based on local normal force control. Test results show significant relative improvements in levels of surface roughness and a reduction in the normal spatial variation.

Keywords: Grinding; Control; Silicon.

1 Introduction

The rotational grinding process is widely used in the production of silicon substrates for semiconductorintegrated circuits. The fundamental configurationis regarded as optimum for producing large diameter substrates that meet industry specifications for total thickness variation (TTV)and site flatness (SFQR)[1,2].The process is also used for "backgrinding" after microfabrication where the substrate thickness is reduced to a practicable minimum to conform tocritical end-usedesign requirements [3,4]. In both "back-end" and "front end" variants of the process, minimisation of surface roughness and subsurface damage, is always a critical driver in order to maximise the structural integrity of the substrate and minimise the significant costs of subsequent processing [1,5].

The process engenders by definition [1] a very specific machine and tool configuration, shown schematically in figure 1. It comprisesnominally parallel but offset axes of rotation of tool and work with unilateral engagement of the work surface as shown. In the most common mode of operation, the infeed(f) and infeed rate(df/dt) are controlled to remove a preset depth of cut andimpart a specified surface finish. The simple geometry and kinematics ensure that flat surfaces are generated independently of the tool surface profile depending only on the alignment of the axes of rotationand assuming infinite machine rigidity [6].

However, the simple configuration is characterised by inherently varying local kinematics as clearly the workspeed (v_w) varies as a function of radial distance, r, from the centre of rotation of the work. The effect of this has been modelled and simulated to predict surface roughnessand chip-scale parameters [7,8,9] while, experimentally, local normal forces have been measured by integrating a miniature piezoelectric force in the force flux of a single grinding segment [9,10]. Varying levels of surface roughness and subsurface depth of damage have also been confirmed experimentally [9,11] while variations in TTV and planarity are also possible on machines of non-infinite stiffness whereelastic deflections are present at the end of the machine cycle [9,12].

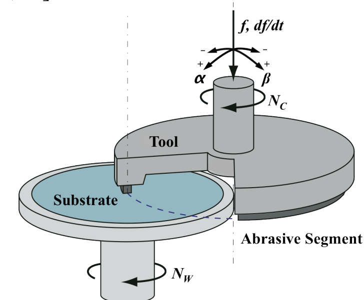

Fig. 1. The rotational grinding configuration

The effects of the varying local kinematics may be substantially attributable to the normal force variation noting that, per Hahn [13], the "true input to the grinding process is the normal force". Hahn also added that the normal force is "uncontrolled on conventional grinding machines". Of course, research into the fundamental mechanisms in grinding semiconductor and other brittle materials has shownthat the normal force affects, not only material removal rates, surface roughness and subsurface depth of damage, but also the critical transitions from ductile to brittle mechanisms and between brittle crack modes [14,15,16].

These considerations have provided the motivation for the present work which describes an approach to controlling the local normal force in rotational grinding in particular with a view to assessing the potential to improve surface finish and integrity.As

the approach is based on control of such a fundamental parameter, it may be regarded as an alternative development strategy to precise and predictable "position control" and applicable to lower precision class machines.

2 System Description

The fundamental objective of the system design now described is the realisation of a dual mode of operation in rotational grinding;a normal "infeed mode" and a "local normal force control" mode.The objective and primary functional requirement in the second mode of operation is repeatable high resolution, and high frequency response, control of the normal forcetemporally and spatially (as a function of radial distance from the centre of rotationof the work). For "proof-of-concept", it was designed for integration and testing on thebespoke rotational grinding set-up shown in figure 2 realised by modification of an ultraprecision turning centre (Hembrug).

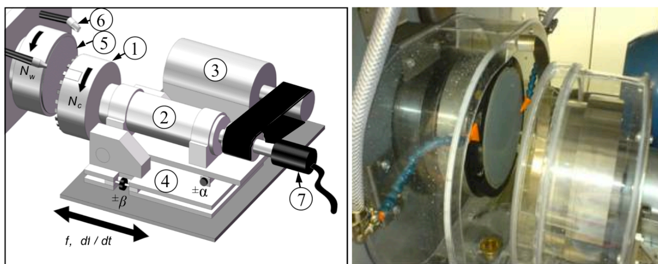

Fig. 2. Rotational grinding set-up / machine platform.

The end-of-spindle assembly (1) is mounted on a GMN precision grinding spindle (2), with an axial and radial run-out <1 µm. A 4kW AC induction motor under inverter control drives the spindle (3) and provides speed range of 1200-5000 RPM. The spindle and motor are rigidly mounted to a base providing independent adjustment of axis alignment (α andβ) (4). A 200 mm diameter porous ceramic vacuum chuck(5) provides rigid fixing of the silicon substrates and a work speed range of 1-500 RPM. Coolant is supplied with a variable flow rate to the inside and outside of the tool (6). Connection to the force sensor and actuators is facilitated through a multi-conductor slip ring unit (7).The Hembrug turning centre provides high resolution CNC infeed and infeed rate control over a wide range.

In terms of realisation of the design objectives and specific functional requirements, the identification of a basic technology to realise dynamic closed loop force control was critical. The adopted solution is shown in figure 3 and comprises a preloaded piezo-actuator driving a flexure plate with affixed abrasive segment in one degree of freedom. In order to establish "proof of principle", evaluate the core micro-actuator technology, and enable modular development, the configuration shown in figure 4 was realised. It comprises two micro-actuator drive units; a "lead actuator" per figure 3 and, mounted diametrically opposite, a "lag" actuator, which is otherwise similar but for the force sensor. The other segments shown are fixed and, when the two micro-actuator segments are retracted, the tool is driven in the normal single "position control" mode involving infeed under the machine CNC control followed by a preset "sparkout" time.

A dual mode (DM) machine cycle is shown in figure 5. The "force control or finishing mode" is implemented after a "normal" single mode sequence under machine CNC control or, more specifically, after "sparkout" and retraction of the tool by some microns. The micro-actuator driven segments are then extended and controlled as a function of tool angular rotation,determined by timing with reference to a proximity sensor, to generate the programmed normal force; providing also for the lag between the two engaging segments. In view of the reduced number of engaging segments in this mode, the speed of rotation of the work is reduced pro rata to realise geometrically similar "swept areas" by the segments. The control software for the system was based on an empirical model relating the required normal force to the piezo-actuator controller input voltage but depending on the tool speed, the work speed and the monitored radial distance from the chuck centre of rotation. Due to constraints on controller processing speed, a low tool speed (1250 RPM) was found to be necessary to ensure repeatable force control.

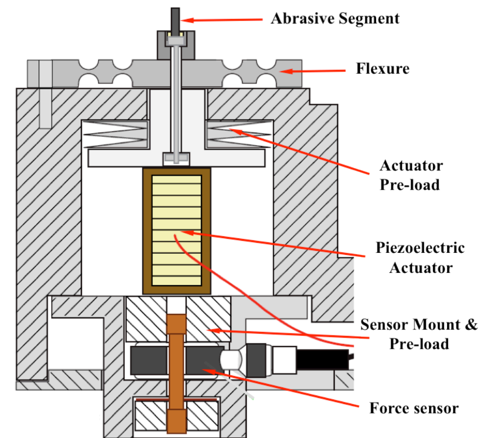

Fig. 3. Dual mode control module-lead actuator configuration.

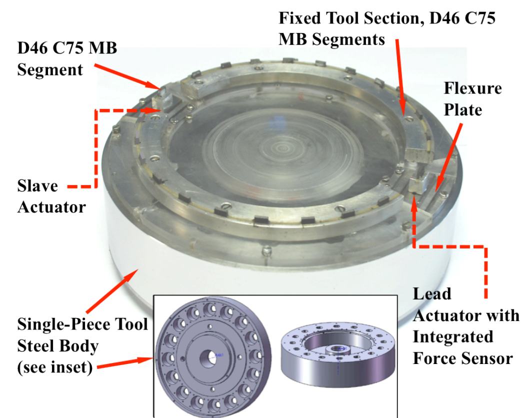

Fig. 4. Dual-mode control "intelligent tool".

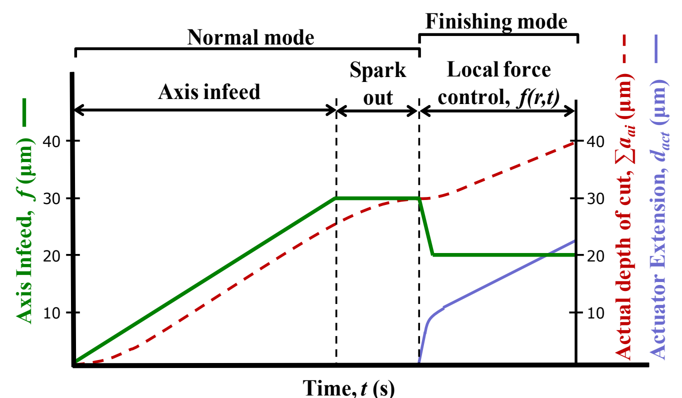

Fig.5.Dual mode machine cycle.

3 Experimental Programme

3.1 Process Capability / Single Mode Cycle

The baseline for assessment of the dual mode system is the performance, or process capability, of the standard single mode of operation. The process conditions that apply are shown in table 1 based mainly on preliminary optimisation and the tool manufacturers recommendations for backgrinding silicon. The tests involved monitoring force profiles at intervals during infeed and measuring surface roughness (R_a) on samples produced under these conditions. The reproducibility of these results was also assessed to determine in particular if the tool "sharpness" was reasonably constant.

Table 1
Optimised process parameters

Tool Specification	Type 2A2, Φ200 mm, D46, C75, proprietary metal bond, 22 segments, 2*8 mm
Work Material	Φ200 mm, <100> orientation, Epi grade silicon, ground finish (<1 µm R_a)
Infeed, ***f***	30 µm
Infeed rate, ***df/dt***	1 μms^{-1}
Sparkout time	30 secs
Work speed, N_w	100 RPM
Tool speed, N_c	1250 RPM
Coolant	Process water, 4 $Lmin^{-1}$/ nozzle

*3.2*System Performance / Capability

The objective here is to assess the DM "system capability" by determining if the normal force can be controlled,as a function of the radial position, to programmed levels, with a level of variation that is significantly less than the range of variation in a "standard" (SM) machine cycle. For the purpose of this research the objective was to show that a constant local normal force could be maintained during the finishing cycle. In this case, force levels of 1 and 4 N were to be maintained.

3.3 Dual Mode Comparative Tests

A series of randomised comparative tests were implemented alternating between two dual modes of operation; DM, the dual mode shown in figure 5 involving "constant force" finishing at 1N for a fixed time interval (shown to remove >10 µm depth of cut) and, DF, a dual mode cycle but a standard single mode cycle is followed by an equivalent constant low infeed rate for an equivalent interval (an infeed rate of 0.16 μms^{-1} with N_w at 100 RPM to realise a similar depth of cut per rotation, a_e, for the same number of rotations).

As indicated, the immediate interest is in the potential for improved control of surface finish. The surface roughness was measured on all samples after an ultrasonic cleaning procedure. Both stylus (Taylor Hobson Talysurf2) and white light interferometry (Veeco) instruments were used to measure surface roughness at 20 mm intervals from the substrate centre and in a fixed crystallographic direction (relative to the notch). Three stylus measurements were taken in a "tangential" direction.

4 Results

4.1Process Capability / Single Mode Cycle

Figure 6 showsthree normal force (F_N)profiles sampled at about 10, 20 and 30 µminfeedunder "standard" grinding conditions as defined in table 1 and inset in the figure. There is no significant difference between profile samplings, noting also that the levels shown were arrived at after 3-4 µminfeed and reduced to near zero by 4-5 s into sparkout. Also, the profiles shown were found to be repeatable and reproducible thus exhibiting constant "sharpness" and supporting the manufacturers claim that the tool is self dressing for grinding silicon.

Figure 9(SM) shows average surface roughness levels (roughness average, R_a) at the indicated radial distances based on 5 samples produced under the same "standard" conditions in repeat machine cycles. These results are a baseline for subsequent tests.

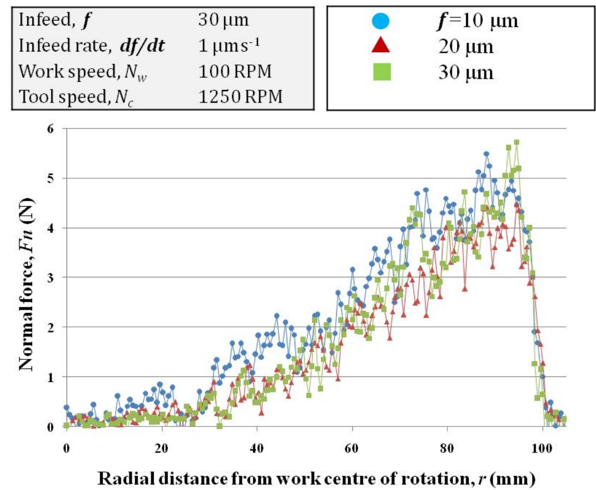

Fig.6. Normal force profiles during a "standard" machine cycle

4.2 System Performance / Capability

The system performance is indicated by conformance to the primary functional requirement. This is demonstrated in figure 7 by normal force measurements as a function of radial distance, *r*. The average and standard deviation shown is based on 10 profiles sampled at equal intervals in the "finishing" mode with 1 and 4 N presets.

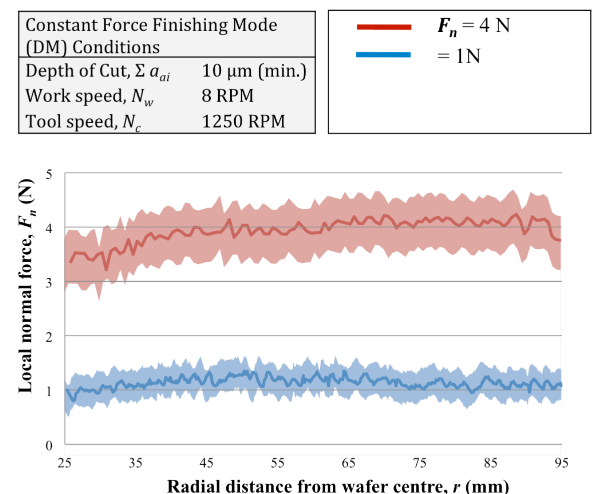

Fig.7. Control of normal force during finishing in a dual mode cycle

4.3Dual Mode Comparative Tests

Figure 8 shows the surface roughness results from the randomised tests to compare the two modes of operation being: DM, the "constant force" finishing mode at 1N and, DF, the low

constant infeed rate finishing mode. It is shown that there is a significant difference between the two sets of results with levels of surface roughness produced in the DM mode reduced and less absolute variation with radial distance. These results should be considered in the context of the actual depth of cut during the finishing phase which for the DM mode ranged from 10 to 12μm and, for the DF mode, ranged from 5 to 11μm.

Constant Force Finishing Mode (DM) Conditions	
Normal Force, F_n	1N
Work speed, N_w	8 RPM
Tool speed, N_c	1250 RPM
Depth of Cut, $\Sigma\, a_{gi}$	10 μm (min.)

Constant Infeed Finishing Mode (DF) Conditions	
Infeed Rate, *df/dt*	0. 16 μms^{-1}
Work speed, N_w	100 RPM
Tool speed, N_c	1250 RPM
Fin. Mode Time	DM Equiv.

DM1
DM2
DM3

DF1
DF2
DF3

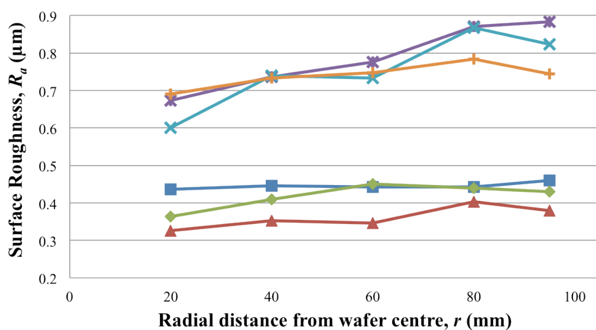

Fig. 8. Comparison of surface roughness profiles on samples produced by constant force (DM) and low constant infeed (DF) finishing

In order to investigate further, the change in R_a during a DM finishing cycle was found as a function of the (measured) depth of cut. The results are shown in figure 9.

Constant Force Finishing Mode (DM) Conditions	
Normal Force, F_n	1N
Work speed, N_w	8 RPM
Tool speed, N_c	1250 RPM
Depth of Cut, $\Sigma\, a_{gi}$	Variable

SM
DF
DM-4μm
DM-8μm
DM-11μm

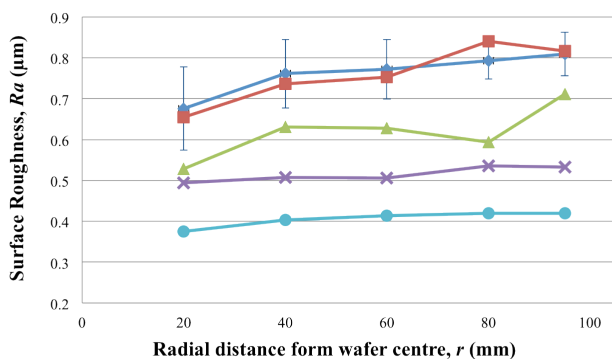

Fig. 9. Comparison of surface roughness profiles produced under standard (single mode, SM) conditions, low constant infeed (DF) and constant force (DM) conditions vs. depth of cut.

5. Discussion

The improvement in surface roughness levels shown in figure 8 was supported by visual comparison of areal surface micrographs. It wasconcluded from these observations that the level of brittle fracture on samples produced under constant (1N) force is significantly reducedimplying also an improvement in surface integrity.The underlying mechanisms that result in consistent and significantly higher levels of surface roughness under infeed control, may be elucidated by observations on the normal force variation during infeed. It was observed that the normal force increased up to a level of about 2N and then reduced rapidly. It is postulated that this is at a level where brittle fracture is more energetically favourable.

6. Conclusion

A novel dual mode control system for rotational grinding has been described. It enables operation on the basis of (normal) infeed control and or on the basis of local normal force control. It has been shown that levels of surface roughness can be significantly improved by following a normal machine cycle with a low normal force finishing mode.

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