Etch rate prediction for Ion milling machines

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1 Introduction: The Problem

SAE Magnetics Ltd. produces read/write heads for hard disk drives. These tiny devices are mounted on arms inside the hard disk drive, and are designed to fly a few micrometres (μm) above the spinning disk surface. The head converts electrical signals to and from magnetic fields that interact with the magnetic material of the disk surface, reading or writing data onto the surface. The distance between the read/write head and the disk surface must remain constant for reliable operation. The heads are therefore designed with a specific aerodynamic profile that must be etched out of the material making up the heads. The heads are fabricated in large numbers within a wafer of magnetic material, similar to the manufacture of integrated circuits from silicon wafers, before the wafer is broken up into individual heads.

The aerodynamic profiles are etched into the wafers inside an ion milling machine. Etching takes place by bombarding the surface of wafer with ions of a gas, typically argon or oxygen. The ions are accelerated to very high velocities by electrostatic forces. Prior to etching, the wafer surface is partially coated with a layer of material called a resist that protects some areas of the wafer while exposing others. After milling the resist is stripped off, leaving a pattern of eroded grooves in the wafer material.

Milling is a "one shot" process. The wafers are placed at one end of a vacuum chamber (see figure 1). Up to four wafers may be processed simultaneously by placing them on a jig that slowly rotates, exposing each wafer to the ion beam in turn. The etching depth is controlled simply by the amount of time spent by each wafer in the ion beam before the wafers are retrieved from the chamber. The wafers are then tested, and any wafers not etched to the desired depth must be discarded.

Efficient production therefore requires an accurate prediction of the etching rate. Wafers of different materials will be processed in a working day, using different protective etch resists, different gases, different accelerating voltages, and different inclinations between the wafers and the ion beam. Between milling runs, the machine is idle for a certain time, known as the "stop time". There is evidence for an increasingly erratic etching rate when the milling machine is restarted after longer stop times (see figure 2). The data supplied by the company suggest a time scale on the order of 20 minutes characterises the onset of the problem.

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SAE Magnetics Ltd. asked for a model to throw some light on this erratic behaviour.

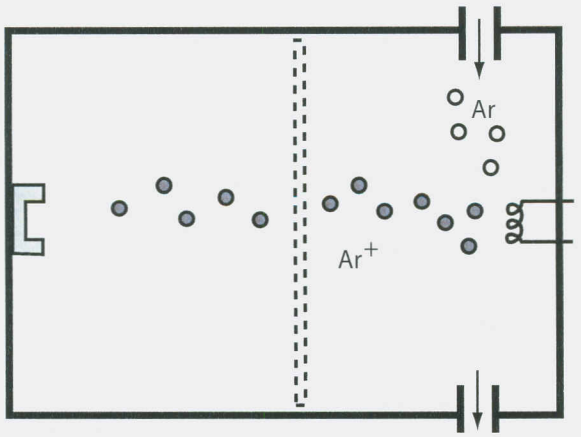

Figure 1: A schematic of the ion milling machine. Neutral gas introduced into the chamber is ionized at the hot tungsten filament, then accelerated by electrostatic forces through a screen towards the work piece at the far left. The ions blast into the material, milling away tracks and grooves wherever the surface of the work piece is not protected by a coating of etch resist.

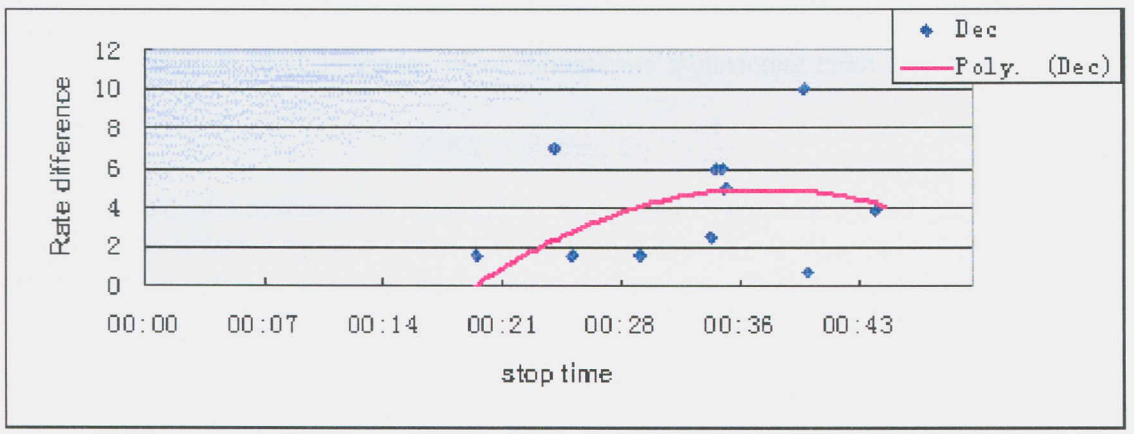

Figure 2: Onset of unpredictable etching rates occurs after a characteristic stop time on the order of 20 minutes, and the scatter seems to grow worse with increasing stop time. Figure supplied by SAE Magnetics (H.K.) Ltd.

2 Physical Parameters

We begin by noting some orders of magnitudes for parameters and relevant physical processes inside the milling machine. Our discussions were informed by a laboratory manual for ion milling machines provided by the University of California at Berkeley. [1]

The chamber operates at room temperature (roughly 300 K) except for the tungsten filament, which has a temperature on the order of 1000 K.

Ion milling machines run at very low pressures, a typical pressure being $p = 2 \times 10^{-5}$ torr.[1] One torr is the pressure required to support one millimetre of mercury,

$$1 \text{ torr} = \frac{1}{760} \text{ atm} \approx 133 \text{ Pa}. \tag{2.1}$$

The torr is the conventional unit of pressure in high vacuum applications, and the standard atmosphere is defined to be exactly 760 torr. The pressure inside the milling machine in SI units is thus of order

$$p = 2 \times 10^{-5} \text{ torr} \approx 2.6 \times 10^{-8} \text{ atm} \approx 3 \times 10^{-3} \text{ Pa}. \tag{2.2}$$

The last conversion reflects the relation 1 atm $\approx 10^5$ Pa. At this pressure the mean free path λ (the typical distance which a gas molecule travels before colliding with another gas molecule) at room temperature is

$$\lambda \approx 2.6 \text{ metres}, \tag{2.3}$$

substantially larger than the size of the vacuum chamber. A randomly moving particle therefore typically crosses the inside of the milling chamber several times, colliding with the walls each time, before colliding with another particle.

The typical particle velocity is a function of temperature only, about 400 metres per second for a monatomic gas at room temperature.

The ions are accelerated by potential differences between the grid and the wafer on the order of one kilovolt. The velocities achieved through electrostatic acceleration are very much larger than the thermal velocities. The conversion between electron volts and temperature is [2]

$$1 \text{ eV per particle} \approx 11604 \, \text{K}, \tag{2.4}$$

using Boltzmann's constant $k \approx 1.38 \times 10^{-23}$ Joules per Kelvin to relate energy with temperature. In more familiar terms, room temperature corresponds to an energy of $1/40$ of an electron volt per particle,

$$\frac{1}{40} \text{ eV per particle} \approx 290 \, \text{K}. \tag{2.5}$$

The electrostatic energies in the milling machine are on the order of a electron kilovolt, some 4×10^4 higher than the thermal energies at room temperature. Since energy is proportional to velocity squared, the velocity imposed by electrostatic acceleration is thus some 200 times the typical thermal velocity.

The ions move coherently in the beam, not because ion-ion scollisions are effective at smoothing out thermal variations in their individual velocities, but because the imposed electrostatic acceleration completely dominates the random thermal motion of the incoming gas.

Whether or not the ion bombardment produces etching depends on whether the energy per particle in the beam exceeds the binding energy between atoms in the target wafer, and whether the ions effectively exchange energy with the wafer when they collide.

3 Production of debris

Each successful ion-wafer collision knocks out one or more atoms of the wafer. These atoms form a mist of debris or "sub-product" that fills the chamber. Some of the debris will be pumped out of the chamber by the vacuum pump, but some debris presumably deposits itself onto the walls of the chamber, or on working parts like the accelerator grid.

That the debris concentration hinders the milling rate can be inferred from the data in figure 3) supplied by SAE Magnetics. The etching rate is observed to down when more wafers are present, presumably because the debris concentration somehow disturbs the flux of ions onto the wafers. We assume that the debris concentration is proportional to the area of unprotected wafer, and that this area is proportional to the number of wafers in the chamber.

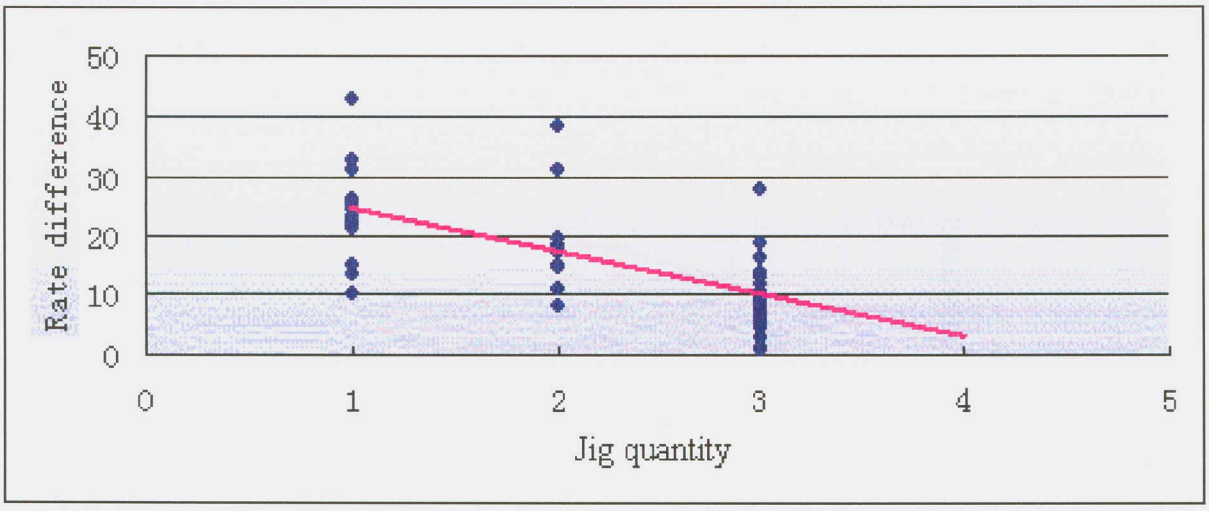

Figure 3: Differences in milling rate for different numbers of wafers present in the chamber simultaneously. Figure supplied by SAE Magnetics (H.K.) Ltd.

We consider the debris to be present in the chamber in two states: (1): bound debris, which is loosely (re)combined debris binding to the walls or other solid surfaces of the chamber. Denote the thickness of the bound layer of debris by the variable g which is a function of time. (2): free debris, which has just been knocked out of the target matrix or out of the bound debris state, and is free streaming about in the chamber. This state is characterized by a number density n, measured in number per volume.

In this model the two debris states have quite different temperatures. The bound debris is in thermal equilibrium with the chamber walls and thus is at room temperature, whereas the free debris may be expected to inherit the very much larger velocities associated with the ion beam.

When the ionising coil is switched off, we take the debris thickness g to be governed by a crude number balance equation:

$$\frac{\mathrm{d}g}{\mathrm{d}t} = \frac{1}{\tau}(g_0 - g) \tag{3.1}$$

where g_0 is proportional to n, the number density of free debris.

Debris build-up bears some resemblence to the process of epitaxy.

4 Epitaxy on the chamber walls

Epitaxy is the process by which material (molecules) is added to a crystalline substrate slowly building up molecular layers. This can take place both in solutions and in gas, the latter known as vapor phase epitaxy.

Vapour phase epitaxy experiments normally takes place at considerably higher pressures, 50 to 500 $\times 10^{-3}$ torr (about 1000 times higher than the milling chamber pressure, though still a tiny fraction of atmospheric pressure), and also at slightly higher temperatures, 450 K instead of 300 K. On the other hand, if the debris atoms leave the wafer with velocities comparable to the incoming ions, the debris atoms velocities are hundreds of times higher than typical thermal velocities in vapour phase epitaxy. Moreover, at the lower pressure all the debris atoms may be expected to collide with the walls, since the mean free path is much larger than the distance to the walls. The mass flux of debris atoms colliding with the chamber walls may therefore not be too dissimilar to that seen in epitaxy experiments.

If we assume that n is roughly constant during a stop period, the value of g governed by (3.1) rises first linearly, then levels off at the value g_0 (see Figure (4).)

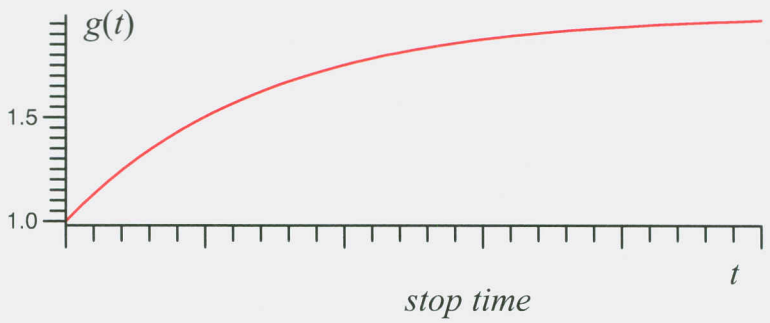

Figure 4: A solution curve to (3.1) rises linearly from 0, then asymptotes to g_0.

When the ionising coil is switched back on after a stop period, radiation from the coil might be expected to heat loosely bound debris on the walls, causing it to fly back into the chamber and disrupt the milling. Additionally, the ions from the beam may also loosen wall bound debris, adding further to the debris density.

If we take the data from Figure (3) to indicate a linear decrease of (the average) milling rate r with increasing number density n,

$$r = r_0 - \alpha n$$

and further assume that a higher value of the thickness g leads to a higher value of n immediately after a stop period, we get a rate differences as a function of stop times as depicted in Figure (5).

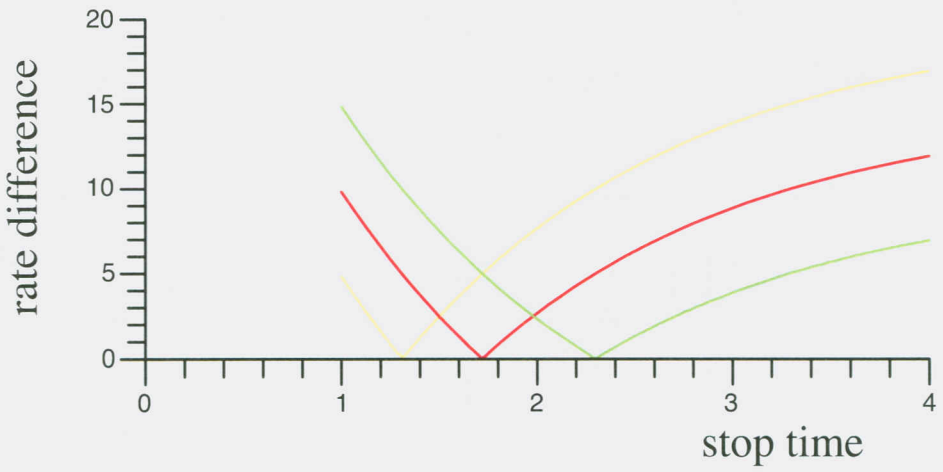

Figure 5: Absolute value of the rate difference as a function of stop time, for the model where number density following a stop time is proportional to the solution of equation (3.1).

This behavior is in qualitative agreement with the SAE Magnetics data in Figure 2.

In this model, longer stop times will always lead to increased rate differences, because longer stop times lead to more debris build-up; the only way to control the problem is to inhibit the debris build-up, by modifying the rate constant τ in equation (3.1).

One way of doing this is to consider the temperature dependence.

The known ([3], [4], [5]) temperature dependence of vapor phase epitaxy growth rate is sketched in Figure 6.

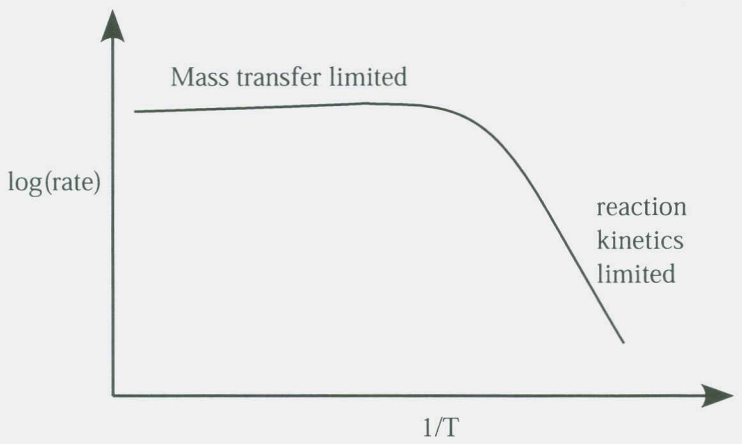

Figure 6: Epitaxial growth rate as a function of (inverse) temperature of bound substrate. Typical growth rates are 1 to 10 nanometres per second.

For sufficiently high temperatures, the growth rate is nearly constant, limited only by the mass transfer from gas to solid, i.e., the rate at which gas molecules can be made to impact on the walls.

On the other hand, the lower the temperature of the wall, the better the wall 'repels' an impact from a free flying debris atom, and the slower the build-up of debris on the wall. At low temperatures, we expect the build-up rate to be limited, with a Boltzmann factor that depends on temperature as

$$\frac{1}{\tau} \sim e^{-E/kT}$$

In the Ion Milling Machine this means that for given stop times, the lower the wall temparature, the less build-up of residue will take place during the stop time.

5 Conclusion

An epitaxial-like process of debris build-up both during operation and during a stop time may be expected in the ion milling machine.

If the behavior of Figure 2 is caused by release of debris from the walls, the observation of more instability for longer stop time is consistent with debris building up over time.

One way to reduce the problem is to inhibit the build-up of debris. From Figure 6 one can see that a reduction in temperature should decreases the rate of debris build-up.

Based on the possible model analogy with epitaxy, we propose then that a way to suppress build-up of debris layers on the walls during stops is to *cool the walls*.

References

[1] Microfabrication Laboratory Manual, University of California at Berkeley, chapter 7.14 – Ion Beam Milling.

[2] M. Danos and J. Rafelski, eds., *Pocketbook of Mathematical Functions* (Verlag Harri Deutsch, Frankfurt, 1984).

[3] G. Stringfellow, *Organometallic Vapor-Phase Epitaxy, Theory and Practice* (Academic Press, Inc., San Diego, USA, 1990).

[4] D. Hurle, ed., *Handbook of crystal growth. Vol. 3: Thin films and epitaxy* (North-Holland Elsevier Science Publishers, Amsterdam, 1994).

[5] K. Jensen, D. Fotiadis, and T. Mountziaris, *Detailed models of the MOVPE process*, Journal of Crystal Growth **107(1)**, 1 (1991).