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Thermodynamic considerations in wire saw processing

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ABSTRACT

The last several years have seen a significant number of publications on wire saw data in regard to process optimization theory applied to solar wafering. The methods vary, but fundamentals concern the mechanical dynamics of the wire sawing process, where measurements of the wire forces in the silicon slot using free abrasive are studied; however, these data are not yet fully correlated to a complete thermodynamic analysis of the problem. The objectives of the empirical development of the process theory are also widely varied, but there is industry agreement that it is being faced with the fundamental limits of cutting rates in processes that use free abrasive slurries and a single wire. The limit arises from intrinsic thermodynamic limits of the delivery of work energy to the silicon slot. Similarly, these same principles prevent us from increasing the wafer load to overcome the limitation as work energy transfer rates are countered by higher entropic losses that occur as power and wafer load are increased. The effect results in the problem that the wafer load may not be increased without proportionately reducing table speed. The fundamental nature of these limits suggests that they involve theoretically calculable energy quantities of thermodynamic limiting functions, which restrict the 'useful' work that we can extract from the system, where the work energy of interest is the abrasion of the silicon in forming the wafers. The present work reviews the theoretical issues of determining process efficiency optimums that could be used to achieve throughput gains.

Introduction

High-volume wafer manufacturing in the solar industry is dominated by the use of free abrasive with multi-wire saws, with a large effort now being made to reduce costs of fixed-abrasive processes to be competitive in this market. Although the standard diamond wire fixed-abrasive process is currently very expensive, it has a cutting efficiency advantage that results in higher throughput. This creates a need in the industry to determine if the limit of future cost reductions in diamond wire can result in overall cost effectiveness. This cost effectiveness would need to exceed the ability to achieve those cost reductions and throughput improvements that remain with free abrasive.

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Processing with free abrasive in a PEG (polyethylene glycol) carrier has become increasingly economical over the past decade as high-yield recycling processes have come to the fore. Recovery of the abrasive and the petrochemical carrier is critical to achieving cost effectiveness. Dealing with the chemical control instabilities that result from variation in the wire saw process, as well as the recycling process, is now an industry education effort, since most wafering companies focus on the mechanical aspects of their sawing process and look to the chemical companies to ensure the incoming chemical control. However, the wire-sawing process optimization and stability concern the joint chemical and mechanical processes which need to be analyzed as a single thermodynamic system. Furthermore, the approach to solutions concerning the optimization of the wire sawing process is generally best regarded as a thermodynamics problem.

Process stability

For complex thermodynamic systems, its best to first consider what components constitute the most complete 'system' to be treated. Following this, the different theoretical issues for each component can be isolated and any errors in assumptions can be identified as they arise. In fact, this procedure of dividing the system into components helps identify energies that can be measured or estimated and those that cannot. As thermodynamic problems are often in regard to linear algebraic structures that divide variables between those with values that can be known from those that are unknown, this allows some solutions to be constructed.

Consider that the thermodynamic system for wafering consists of two distinct parts, (1) mechanical: the wire saw structure, the wire and drive motor, and; (2) chemical: a slurry of PEG carrier and SiC abrasive. If we additionally consider the recycling of the slurry, a thermodynamic cycle can be isolated that only considers the state changes of the slurry, as shown in Fig. 1.

The wafering process runs in cycles of accomplishing the 'useful' work of cutting the ingots into wafers and dumping the waste heat and other entropy to the surroundings. The sum of these is the total available work – known as 'free energy' – of the process. The process is repeated by returning all the system components to their original state and beginning again. For the slurry, this means restoring the available work of the chemical which is measured by changes in the Gibbs free energy, ΔG. There is a variability of the total process that is tied up in the precision with which we repeat the detailed steps of returning to the original state. These include returning the saw table to its original position, and replacing the wire and inserting new ingots; however, none of these pose much of an issue in terms of repeating the original thermodynamic state.

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Nevertheless, returning the slurry to its original state in a recycling process has a significant impact on the total process. As it is not possible to measure all of the free energy changes of the slurry during the cutting process, it is difficult to determine whether or not it has a negative impact on

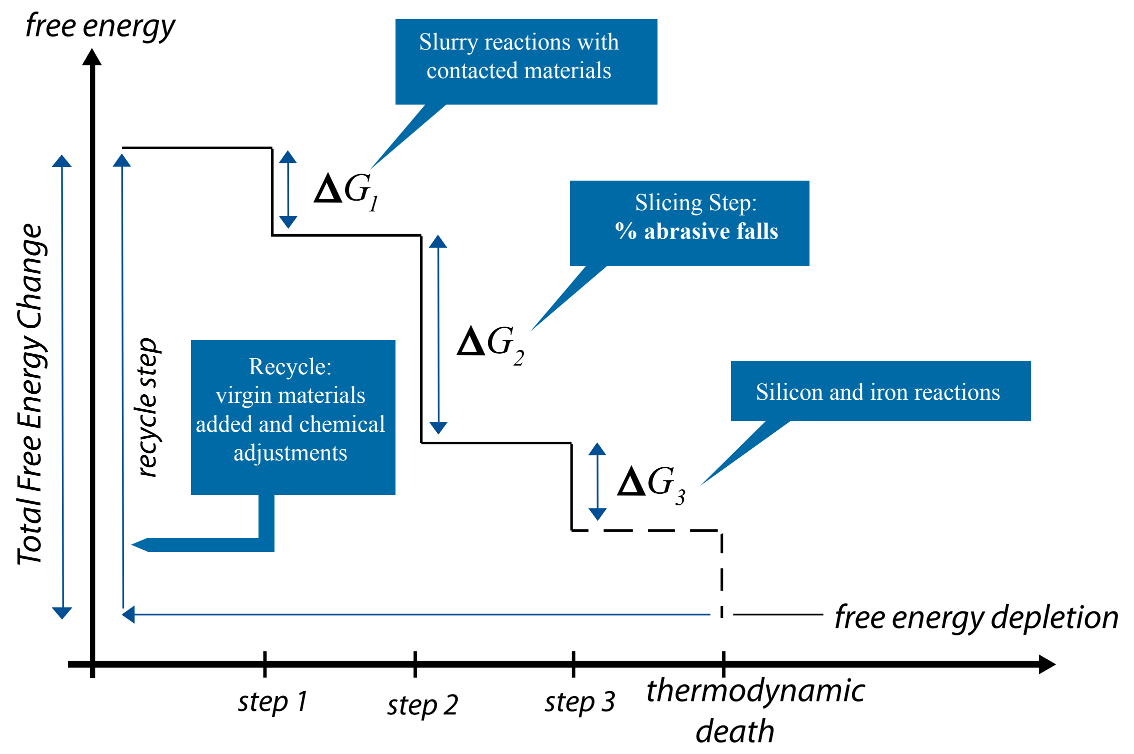

Figure 1. Repeatability of the slurry 'state' changes affects process control run to run. Some free energy declines are chemical state changes that provide no useful work.

the work energy of abrasion in the silicon slot (e.g. certain chemical reactions). However, repeatability of the change in ΔG impacts the overall process control. The largest decline in the free energy of the slurry that impacts the ability of the system to achieve the work of abrasion directly is the kerf rise in the slurry during the slicing operation. The percentage of kerf in the slurry reaches a limit such that the rate of work that can be delivered to the slot must be declining during the slicing operation. This loss of ability on the part of the slurry to accomplish work in the slot can be associated with the rising entropy of dilution of the pure SiC.

This presents a potential problem in terms of assigning the free energies. As the work that the slurry does in conjunction with the wire is mechanical work, the measure of the system's potential to do work is called 'availability' and belongs to a calculation of Helmholtz's free energy, A, for mechanical work. Yet all the entropic losses of the slurry in the diagram are shown to be Gibb's free energy which, it has been suggested, denotes the chemical changes of the slurry. There is actually nothing wrong here. The largest entropy decline of dilution of the abrasive can be reversed by mechanical processes of separating the kerf from the SiC, so we are not prevented from assuming that the ΔG of dilution and the decline in ΔA closely correspond for this particular change. However, the remaining slurry changes are purely chemical, and so do not have a direct correspondence to change in work energy of abrasion. The problem can be solved by devising a test that measures their impact on ΔA. Crucially, we have identified what can be measured or estimated with respect to the chemical changes.

Fig. 2 gives a list of control factors for chemical changes in slurry as it is used in wire saw processing. One measure of chemical process control can thus be defined by the repeatability of the associated free energy changes of all the possible chemical reactions that might occur. The point here is that the total process variation is the sum of the individual variations, so one must either eliminate the source of the variability or repeat it precisely each run.

Defining the thermodynamics for the slicing operation

Our interest lies in determining the maximum work that can be delivered to the silicon slot for a given process arrangement (e.g. length of ingot, length of wire, etc.). There are other criteria for optimization that concern the details of how this work is delivered, so we need to determine precisely what should be optimized. The work function A is the 'availability' of work for a given system arrangement and the intention is to isolate just the process of abrasion for its analysis. The limit of delivering work to the silicon slot as useful work of abrasion is again determined by loss of the available work energy to entropy.

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Unfortunately, determining the maximum of this limit in thermodynamic theory concerns reversible processes alone, which are those conducted at infinitesimally low rates. We may, however, use real rate processes (those that are practical) and make measurements to empirically determine new functions of the limits of the work which can be accomplished for those real processes. The outcome of this type of methodology is that for real processes, the rate of losses to entropy (per unit volume of silicon) rise with power input to the system [1]. So the requirement is to experimentally determine the rate of work against the rate of entropic energy loss for several process conditions. At this point, our objective is to assess a function of these two rates with increasing wafer load. In order to assess this, it is necessary to define the system and properly identify the known and unknown quantities in our estimating procedure.

Possible Control Factors	**Parameters Affected**
- Chemical adjustments at recycle	- pH, chemical activity
- Si and Fe kerf level in reservoir	- chemical reactions
- Kerf level in recycled slurry	- chemical potential
- Interactions with distribution system	- shear forces
	- sluffing of contaminants
	- liquid-solid phase separation
- Viscosity control	- slot width control
	- cutting efficiency
- Slurry lot blending	- lot to lot consistency
- Ingot temperature	- temperature variation and entropic effects
- % water control	- saw marks, chemical activity
- minimize contacted materials	- chemical reactions
- Slurry heat capacity & heat ex settings	- high temp in saw
- Abrasive loading	- saw performance
- reservoir replenish control	- kerf level consistency, pH consistency
- kerf level in reservoir	- chemical reactions, saw marks

Figure 2. Factors Which Vary Total ΔG

To this end, the silicon abrasion process is analyzed, where there is work being done on the ingots plus heat lost to friction in the silicon slot, and the sum of these must amount to the energy change of the system occurring at only the point where this type of work is being done. This leads us to the following, according to the energy conservation principle which is the first law of thermodynamics:

$$\Delta E_{\text{system}} = q_{\text{out (friction)}} + w_{\text{in (abrasion)}} \qquad (1)$$

This is simple enough, but the heat lost to friction is for the silicon abrasion process alone and we must avoid confusing it with other heat losses that need to be identified within the remainder of the system, and those that do not belong to the ΔE of this defined system alone. Here, E only concerns the energy spent in the silicon slot, directly associated to the work at the silicon interface. If we consider the wire motor that supplies the energy as having its own loss of heat to the surroundings in its operation, it is only the portion of the motor's energy not lost to heat that can be said to result in the work energy. The contribution of the motor to the work energy is reduced further by the energy spent on moving the wire web,

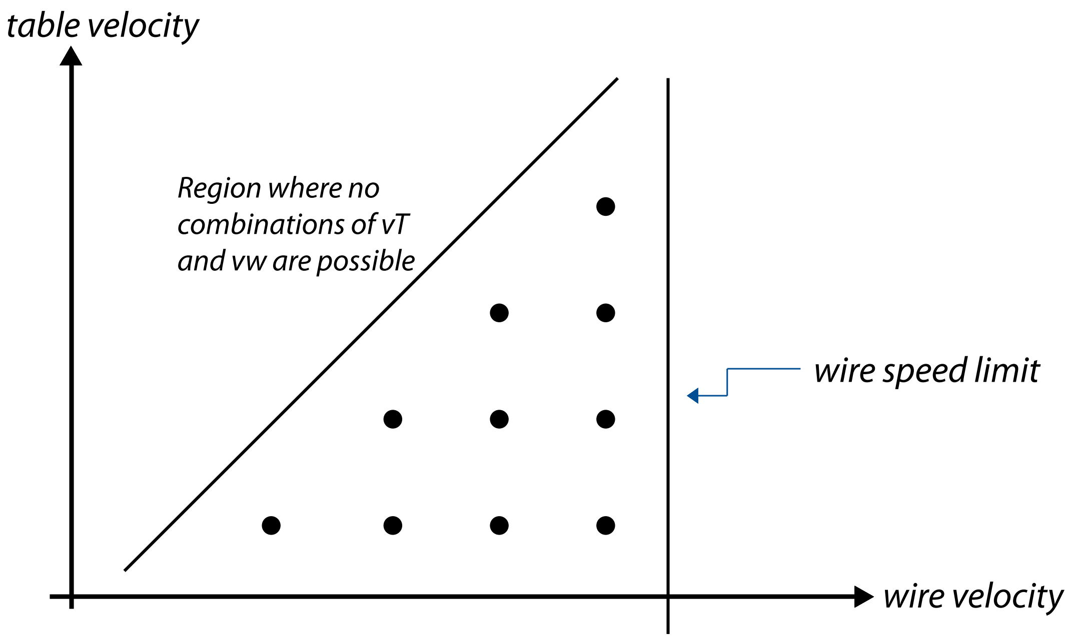

Figure 3. Free abrasive slurries are restricted by limits of rates at which the wire can deliver work energy to the slot. As silicon load and system power increases, table speeds must be lowered due to rising entropic losses which further reduces the work energy delivery rate.

or the energy associated with the web's motion when it is not cutting. This energy needs to be excluded from the energy of the abrasion. It is important to remember that energy ΔE is internal energy and it is independent of any physical part of the system or surroundings; hence, it denotes the energy transformation alone, and occurring precisely within the defined system and not outside of it.

By now, one can see that there are several divisions of the total mechanical and chemical system which all have separate energy considerations associated with them. At this point we have no ability to form an optimization function from the first law energies alone, and only thermal efficiencies can be calculated from this data. Instead, we require a function that accounts for the sum all the entropic energy losses that occur across the boundary of the system.

The work function and process throughput

Now consider the problem of what limits the ability to increase the throughput of slicing. Given a sufficiently small ingot, cuts can be run at extremely high table speeds of 800µm/min or more. So what change in dynamics is occurring at large production loads that limits our processing below, say, 400µm/min? Fig. 3 shows that there is a range of working ratios of the velocity of the table and the horizontal wire velocity, (vT/vw). The limit of achieving high vertical table speed indicates there is a limit to the rate at which work is delivered to the slot by the wire.

But as the table speed must be reduced when the silicon load is increased, regardless of the wire speed, we must look at what mechanisms are degrading the ability to deliver the available work energy to the slot. It is obvious that the wire itself is being abraded and loses a large percentage of its mass by the time it reaches the last wafers on the table, so there is momentum reduction occurring. However, the problem with the end wafers (wire marks, etc.) is only an indicator of the approaching load limit which is being caused by falling work energy across all the silicon slots. Degradation of the rate at which work is done is occurring from all sources of entropic loss and the wire abrasion is only one of these sources.

The second law of thermodynamics allows us to assess all the sources of entropic loss in one term and gives a unifying principle that the resultant work energy of abrasion will be equal to the change in work availability ΔA, minus all of the entropic losses. Further, as power of the system increases (ingot load), the system moves further away from an ideal reversible process; however, all entropy loss as a proportion of ΔA will rise by a function that can be determined empirically. At this point, regardless of whether or not all of the sources of the entropy can be known or measured, the total and its rate of change can be determined because of the second law requirement of the balance of these energies.

Optimization principles

Regardless of the particular experimental approach, some method is required to provide values for only the abrasion process in determining the work energy of abrasion. We further wish to eliminate the vast potential for errors in energy accounting when doing this. The value is obtained either through direct measurement, or from calculation where knowing the internal energy change and heat loss determines the work energy. Any optimization function will have to additionally account for all the entropic loss mechanisms and not just the sensible heat lost to the friction, since we suspect the optimization problem requires the minimization of the rising entropic losses as the size of the silicon load increases.

Now, if we consider ΔE as the energy intensity in the slot, part of it is producing the work of abrasion while another part is producing heat of friction (solid-to-solid and friction of viscosity). If we search for conditions that maximize the intensity in the slot and simultaneously produce the largest slot, we might expect that this optimum would be general and produce the most work in the slot despite variation in other parameters. The function that produces this is thermodynamic effectiveness:

$$\varepsilon = \frac{\text{work of silicon abrasion}}{\Delta \mathrm{A}} \qquad (2)$$

where the second law of thermodynamics for mechanical work defines $\Delta A = \Delta E - T\Delta S$.

For this function, whether the work of abrasion rises or the entropic losses ($T\Delta S$) declines, the effectiveness of the process improves. Further, we would expect that whether high loads are cut or one slot is cut with the determined optimal conditions, the maximum work possible is being produced in every slot, even if the work per slot was declining with position on the saw table as the wire wears down.

Now assume the rate of increase in entropy must rise with the rising power (load), so that the average work energy per slot is dropping due to the increasing rate of entropy loss – this is our existing condition for high production throughput. All that can be done in this case is to maximize the average work production rate by setting conditions that minimize the entropic losses, and this counters the effect of wire momentum transfer rates dropping along the series of silicon slots on the table.

In publications by Anspach et al. [2,3], a novel approach involving single-wire slot cuts was conducted to make determinations of process efficiency. These approaches took direct measurements on the horizontal wire force to isolate the work energy required per unit volume of silicon abraded. In this way, the authors avoided explicitly measuring heat losses of either the motor or the friction in the slot and obtained efficiency values for the optimization procedure. In effect, their efficiency measure produces the following:

$$\mathit{efficiency} = \frac{\text{silicon mass abraded}}{\Delta E} \qquad (3)$$

The heat loss is known implicitly since the silicon mass abraded completely determines the work of abrasion. This is a modification of the 'effectiveness' calculation shown in Equation 2, but the net result is similar. The important point to be made is that the method directly determines the direction of maximum work produced in the slot. Since the force directly determined the energy in the slot, none of the entropic loss needs to be estimated because it is not contained in ΔE. Then one can simply assume that entropic losses are reasonably minimized when work is maximized. With suitable modifications, the method could be used for cutting multiple slots, and this data used to determine if efficiency optimums for cutting one slot will result in process optimums that are valid when many slots are cut.

Conclusion

The optimization analysis presented speculates that free-abrasive slurries could be used at higher efficiency conditions to increase the throughput. The increasing rates of energy losses with rising silicon loads are due to intrinsic limits imposed by entropy in the thermodynamic theory. It is not possible for these effects to be analyzed by dynamics alone. It has been shown that it is then necessary, at some point in the analysis of process optimums, to measure the useful work produced by system if any meaningful calculations are to be made from empirical studies.

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Efficiency results published by Anspach, which have been mentioned, show that water-based slurries have higher efficiency, necessarily from the reduced friction of viscosity. Yet other testing shows that we cannot simply implement lower viscosity carriers to achieve throughput gains, since the distribution of abrasive size carried into the slot is reduced, which in turn reduces the work energy in the slot.

A cooperative of companies that includes Avantor Performance Materials, PPT Research and Hoffman Materials in the US are testing additives which modify the liquid's abrasive 'carry' performance in the slot using water-based formulae, thereby maintaining higher average work energy intensity across the slot length. It is probably not lost on the reader that a schema to raise the work energy in the slot will abrade both the wire and the silicon at a higher rate. Thus, a universal objective is the increase of the value of wafers produced per hour at a faster rate than the cost increase (entropy loss) which occurs for achieving that gain. This is simply another way of stating the optimization of the process effectiveness criteria.

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