Title: Should Intel Invest in 450mm Technology? Determining the Competitive Advantage of Fully Adopting 450mm Ahead of Other Firms

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Abstract:

450mm fabs are inevitably going to be built eventually, but as it stands today all firms with the capability to invest in 450mm have expressed intention to hold off, including Intel. Intel therefore has four options: 1) opt out altogether 2) allow another firm to go first and take on the R&D costs 3) run some 450mm fabs and some 300mm fabs until the 450mm fabs cost less to run or 4) fully invest in 450mm fabs right before any other firm. In this essay, a combination of reports by industry analysts, corporate press releases, and interviews conducted with three senior process engineers at Intel are used to support an analysis of the 450mm competitive environment and Intel's opportunity to gain sustained competitive advantage. A Porter model analysis determines that for 450mm fabs the threat of substitution is high if the cost of running 450mm fabs cannot eventually beat the cost of running 300mm fabs, the threat of new entry is non-existent outside of the members of the G450C, the bargaining power of buyers is high after the initial ramp-up period of 450mm technology, the bargaining power of suppliers is highest in the beginning of 450mm adoption, and the rivalry of competitors does not exist until a second firm chooses to build a 450mm fab. Once the context is set for the 450mm environment, an assessment using the Resource-Based View of the Firm determines that the 450mm technology itself is not inherently a sustained competitive advantage, but the experience of Intel's employee workforce would be if they fully adopt 450mm technology ahead of the competition. The essay is closed out with a brief discussion on how lessons from experience with previous wafer size transitions can guide the next one.

Introduction

People have always been able to look to Moore's Law for a simple description of the competition in the semiconductor industry, the prediction that the number of transistors on an integrated circuit would double approximately every two years. This statement is easily misunderstood to refer exclusively to transistor size, or improvement of some specific technology in the manufacturing process, usually photolithography. However, in truth it is really an accumulation of several factors that boil down to one simple thing: cost. Keeping up with Moore's Law really means making the cost per unit area of an integrated circuit twice as efficient every two years. While that often does mean improving the density of transistors by reducing their size, there are other ways to meet that goal that involve radical technological changes. Perhaps the change that creates the clearest defining line between tiers of manufacturers is increasing the wafer size.

Increasing wafer size is a change that has been made several times before, and each time fewer firms have been capable of tagging along for the ride. The next node in this progression is the transition from 300mm wafers to 450mm wafers. One thing that has made 300mm so successful is the fact that so many firms have joined the 300mm ecosystem, making it feasible to maintain that infrastructure. Only a small handful of firms are even capable of moving to 450mm infrastructure, and by now all of them have either backed out completely or expressed intention to wait a few years. With so much hesitation, will the industry be able to uphold this technology? Up until recently, Intel Corporation was the only firm still expressing interest in opening a 450mm fab in the next two years, but even they now appear to be putting things on hold. Intel is still likely to be the first firm to follow through with the transition, but would they succeed being the first to undergo such a risky endeavor? Intel basically has four options to choose from: 1) opt out of 450mm technology before investing too much initially 2) wait for another firm to go first and let them pay the high costs of initial R&D 3) run some fabs as 300mm and some as 450mm until the more firms adopt 450mm and eventually make it cheaper to run or 4) make a full conversion to exclusively 450mm fabs and take on the full weight of the R&D costs. The only option that will give Intel a true sustained competitive advantage is option 4, making a full commitment to a total conversion of all fabs to 450mm. It's a big risk and a high priced investment, but anything short of this path would take away Intel's edge over the competition. The reason is not because of the 450mm technology itself, but rather that the opportunity to gain the human experience with 450mm technology ahead of competitors is the only thing that gives Intel a true competitive advantage.

In the following discussion, I will use the Resource-Based View of the Firm to compare and contrast two resources in question: 450mm technology, and Intel's employee workforce. I will then use the model of Porter's Five Forces to evaluate the challenges faced by all firms interested in 450mm technology during the initial stages of the transition. Taking both of these analyses into consideration, I will discuss what sustained competitive advantage Intel gains by being the first to fully adopt 450mm technology. To support my argument, I will utilize a combination of reports by industry analysts, corporate press releases, and interviews that I conducted with three senior process engineers at Intel, Mani Rahnama, Jack Hwang, and Henry Ma, all of whom have had experience with wafer size transitions in Technology Development. It is necessary to approach this issue from both an internally focused model and an externally focused model because the 450mm market does not yet exist. Speculation of how it will look for one individual firm must include the context of the market that they plan to hypothetically spearhead.

Why Increase Wafer Sizes?

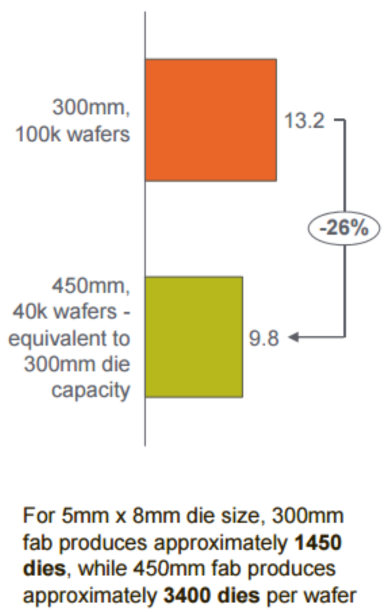
Increasing wafer sizes is an expensive and complicated endeavor. It does not occur as simply an inevitable and natural progression of technology, but rather as a result of a business decision. It will

Figure 1: Quarterly Silicon* Area Shipment Trends

Quarter	Q1 2014	Q3 2014	Q4 2014	Q1 2015
Inches^2 of Silicon Shipped (Millions)	2,363	2,597	2,550	2,637

*Shipments are for semiconductor applications only and do not include solar applications. (Geiger, 2015) only occur if it is predicted to be profitable. Fortunately, profitability-based rationale does exist for it. Electronic devices are on the rise in several markets. Figure 1 shows an increase of the amount of silicon shipped globally, and a record-setting quarter for silicon wafers in Q1 of 2015 (Geiger, 2015). Demand is clearly increasing, and the industry is recovering from the 2008/2009 downturn (SEMICO, 2010). The opportunity exists for firms to seek out competitive advantage in the form of superior productivity.

Figure 2: CapEx per Fab, 22nm Node ($B) (Sonderman, 2011)

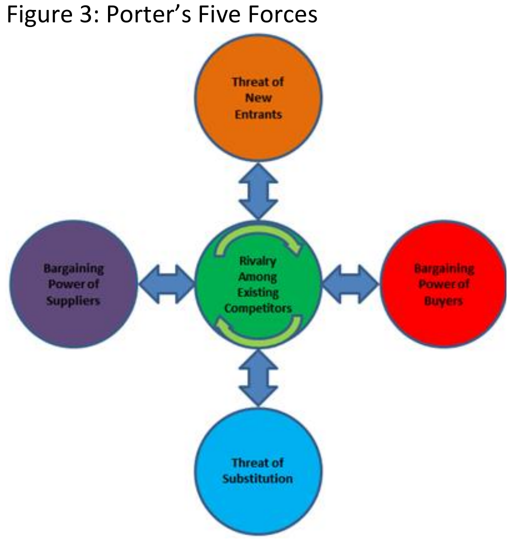


While there are several ways to increase productivity to meet demand, 450mm appears to offer the most realistic options for those at the forefront of high-end microprocessor manufacturing. With the possibility of utilizing so many other new scientific advances to increase efficiency of future products, such as 3D manufacturing, self-assembling polymers, and carbon nanotubes, increased manufacturing capacity is the most essential factor. With more firms going fabless, analysts agree that the "only guarantee in the 450mm conversion is the ongoing need for more capacity," and if the 450mm conversion does not occur, then many more 300mm fabs will have to be built to meet that need for more capacity (Vogelei, 2013). However, there will come a point where building one 450mm fab will be more cost-effective than building two 300mm fabs, and at that point whoever is operating those 450mm fabs maintains a huge competitive advantage (SEMICO, 2010). Analysts at Global Foundries project that the capital expenditures, or CapEx, will decrease significantly per die for 450mm wafers. Figure 2 shows the projected decrease in CapEx for a 450mm fab versus a 300mm fab with wafer starts adjusted to yield the same number of dies (Sonderman, 2011). But, this projection is based on assumptions of factories that exist after the 450mm transition, and that those factories are up and running smoothly. So will anyone take that bet? Porter's Five Forces model may help answer that question.

Porter's Five Forces Analysis

To assess how much an individual firm should invest in 450mm technology, it is necessary to understand what the environment will be like for that competitive field as a whole. Being realistic about who will be the players in the 450mm conversion, only four firms are even considered capable of undergoing such an expense: Intel, TSMC, Samsung, and Global Foundries. Before breaking down each of the Five Forces for the 450mm environment, let us establish what it means to be a competitor in this field. The transition is an elaborate and highly synchronized effort between many interested parties. Therefore, a firm must be a member of the concerted effort of chip manufacturers, or in this case the G450C consortium, which is the most influential consortium in the transition to 450mm technology. The G450C is comprised of the four aforementioned firms and also IBM, SUNY Albany, and the State of New York (G450C, 2015). The contribution of SUNY Albany and the State of New York provides a necessary presence of academic research and government participation, but for the remainder of this paper let us consider G450C to only refer to the five private firms involved, since the goal in the end is to have a field within which these five firms can be competitive with one another.

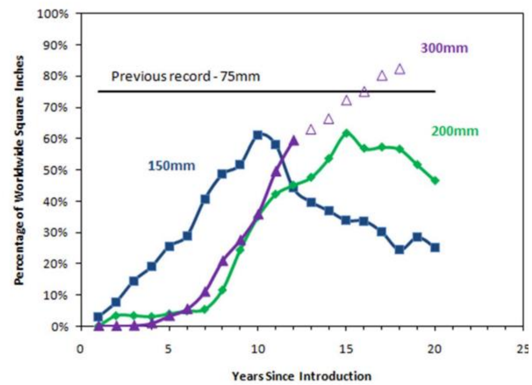
Figure 3: Porter's Five Forces



Threat of Substitution

450mm fabs will only be successful if they are more cost effective than their predecessors. Therefore, the single biggest substitution threat is 300mm fabs, which wouldn't cease to exist just because 450mm fabs go up. Previous wafer sizes still maintain a presence in the industry even as other technologies are introduced (Figure 4). This is actually a serious problem for firms considering the initial 450mm jump. Consider Intel's prospective, for example, who analysts predict is the firm most likely to be the first to make the transition out of the members of the consortium. Even if everything falls into place and all of the suppliers are capable of delivering tools and materials for Intel, the other major chipmakers could choose to back out and continue to operate as 300mm fabs. They would be running very well-established fabs without the challenge of working out the early kinks of a new 450mm technology. That could provide the opportunity to catch up to whatever transistor node Intel is on at the time, overcoming Intel's previous competitive advantage with that node.

Figure 4: Volume Ramp for Previous 3 Wafer Sizes, Years Since Introduction (Jones, 2014)



300mm fabs can still meet the increasing consumer demands for cost effective manufacturing of cheap NAND and DRAM, and they will (SEMICO, 2010). Assuming high-end processors are all produced on 450mm technology, existing suppliers still have the resources to manufacture and further develop 300mm tools. That will improve the quality of those memory-type components being manufactured in 300mm fabs, but it also means that if 450mm proves to be too expensive, then 300mm

Figure 5A Tool Characteistics 300mm vs 200mm

Tool type	Cost	Throughput	Footprint
Expose	1.48	1.0	1.15
Track	1.25	1.0	1.13
Etch	1.18	1.0	1.23-1.50
Thermal	1.19	1.0	1.13-1.28
Implant	1.24	1.0	1.10
Wet	1.73	1.0	1.20
Metrology	1.18	0.62 – 1.0	1.20
Metal	1.40	1.0	1.32
CVD	1.23	1.0	1.30
Spin-On	1.18	1.0	1.20
CMP	1.18	1.0	1.37

Figure 5B: 200mm to 300mm "Real" Cost Savings

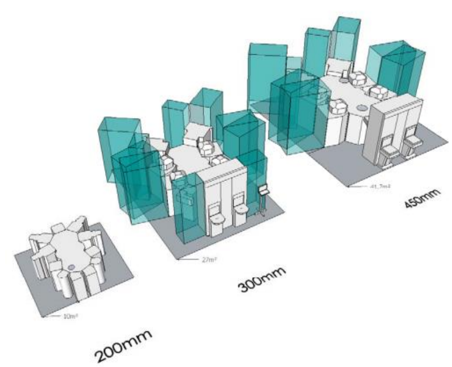
Wafer size	$/waf	$/cm2
200mm	$1,203.17	$3.83
300mm	$1,936.11	$2.74

(Jones, 2014)

fabs from smaller firms could start competing in the microprocessor realm with a now significantly more mature 300mm technology. Once again, this comes down to the cost, which is a realistic threat. Looking at the analogous relationship between 300mm and 200mm, consider Figure 5A, a comparison between cost, throughput, and footprints for various tool types on each wafer size. It is more expensive to run 300mm equipment than it is to run 200mm equipment. What makes 300mm worthwhile over 200mm is shown in Figure 5B, and that is the final cost per cm^2 of silicon, which is 28% lower for 300mm (Jones, 2014). If firms running 450mm fabs cannot achieve that same magnitude of cost savings, then 300mm fabs can easily threaten substitution for 450mm.

Threat of New Entrants

Figure 6: Estimated Etcher Area Size Progressing from 200mm to 300mm to 450mm (Sonderman, 2011)

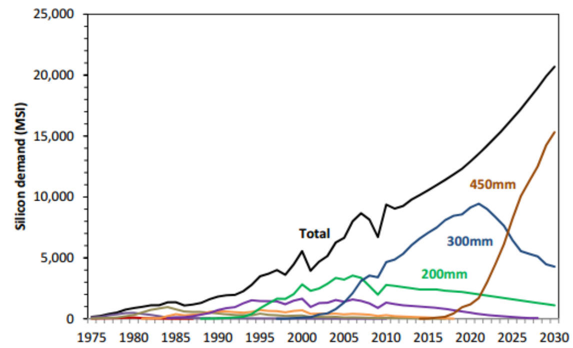


It is one thing to assume that 300mm fabs could substitute manufacturing of microprocessors, but for smaller firms to decide to enter the 450mm realm is a different question altogether. Simply put, nobody can afford it but the current members of G450C. Among many other cost-based factors, the simplest deterrent for new entrants is the fact that altogether new fab facilities need to be built to accommodate the increased footprint of tools (Figure 6). Basically, once the G450C members have all built their 450mm fabs, there is no threat of further new entrants.

Bargaining Power of Buyers

The buyers of 450mm silicon products are a diverse group made up of consumers, governments, universities, businesses, internet service providers, etc., but they all have one thing in common: they want capability (Rahnama, 2015). They want to get the most advanced technology possible for as little cost as is reasonably feasible. The bargaining power of the buyers is therefore at its most critical once the initial ramp up of 450mm is expected to be complete. Once again, if the G450C firms cannot develop products at a reasonable cost for the customers, they won't be able to sell them. The demand for advanced 450mm silicon products exists and is projected to increase dramatically (Figure 7). However, it needs to be met with adequate supply or the price will be too high for buyers to support it. In this way, there is significant buyer power, especially at the end of the initial ramp up period.

Figure 7: Worldwide Silicon Demand by Wafer Size (ICKnowledge, LLC, 2015)

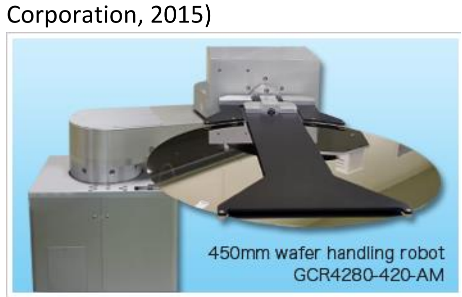


Bargaining Power of Suppliers

The relationship with suppliers is an interesting one because there are several different types of suppliers, even though the goal with each one is to get the same level of certification and specification on new tools (Ma, 2015). In terms of providing materials, for the most part the chemical and gas usage should actually be the same per wafer (Jones, 2014). One thing that is unique about this wafer size transition, though, is that in addition to the G450C consortium of chipmakers, for the first time there is also a consortium of facilities suppliers. The F450C consortium is made up of companies like CH2M Hill, Air Liquide, and Mega Fluid Systems, all of whom hope to be the primary facilities vendors to 450mm fabs. The F450C is designed to collaborate with the G450C to "align on facility standards and necessary infrastructure that drive the cost, duration, safety, sustainability and environmental footprint needed for the transition to 450mm technology" (F450C, 2015). Acting in a concerted effort gives the members of F450C higher bargaining power than if they bid for G450C members' business as individual firms. While the materials essentially do not change, F450C suppliers can charge more in exchange for higher standards, more uniformity across the entire infrastructure, and the promise of greener environmental footprints.

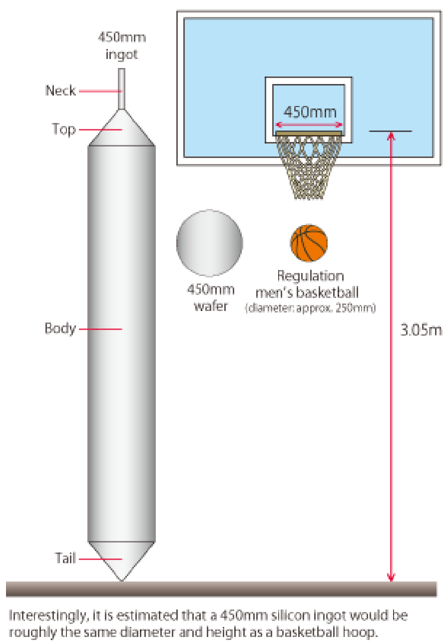
While materials will not change much, in terms of equipment everything needs to be new. With the only customers of the equipment suppliers' products being the members of G450C, suppliers don't have much incentive to develop all new products unless they're being paid top-dollar. Additionally, not many suppliers even have the capacity or resources to develop those new products. The reality is, while Intel appears to be the only member of the G450C that is currently investing in the transition, the few equipment suppliers that are able to join them must demand a high price for their service. On the other hand, if Intel participates in the cost-sharing with equipment suppliers, they also get a large influence on the collaborative R&D effort (Hasserjian, 2012). That means, for example, that metrology equipment manufactured by KLA–Tencor is developed largely to Intel's needs and specifications and not, say, TSMC's. Still, everyone, including other 300mm customers, benefits from the drive to innovate. According to Dave Hemker, senior vice president and chief technology officer at Lam Research, "if you look at the 8- to 12-inch conversion, a whole bunch of the benefits at 12-inch came from things that had nothing to do with the wafer size change" (Semiconductor Engineering, 2014). Often these benefits transcend technologies and everybody has something to gain from the fact that innovation occurred as a result of wafer size change.

Figure 8: Example of new 450mm edge-grip end effector wafer handling robot design by JEL Corporation (JEL Corporation, 2015)



One set of critical challenges with the 450mm transition is the wafers themselves, and the suppliers have a long list of costly challenges to address. Simply consider handling the wafers. First of all, a 300mm wafer weighs 128 grams, with a standard thickness of 775µm. A 450mm wafer weighs 340 grams, with a thickness of 925µm, plus or minus 20µm (LaPedus, 2013). 450mm wafers will warp and bow considerably as they move through the line, which can lead to wafers being dropped when attempting to chuck and de-chuck with an electrostatic chuck (Rahnama, 2015). This means wafer handling robots need to have larger and sturdier

Figure 9: Approximate size of 450mm ingot (SUMCO Corporation, 2010)



chucks, but the chucks still have to be thin enough to fit between the spaces of two wafers in a FOUP, with room to move vertically a few µm to pick up and drop off the wafer in the FOUP slots. Altogether new wafer handling robot designs are necessary to accommodate the sheer size of the wafers and the limited space allowed to move them, such as the prototype in Figure 8 (JEL Corporation, 2015). Even growing the ingots from which wafers are made has new challenges. The ingots for 450mm wafers are nearly twice the height of 300mm ingots, and significantly more waste is involved in the process of growing them (Figure 9). In addition to the challenges of increased size, chip manufacturers are pushing for all possible measures to be taken to slightly increase the useable surface area of the wafer. They are calling for tighter edge exclusion requirements, as well as the introduction fiducial marks rather than notch alignment (LaPedus, 2013). These are all expensive demands, to be frank, and suppliers will be transferring the costs to the chipmakers. “You can’t just tell them to go develop things for you for free, you’re going to have to go write checks” (Rahnama, 2015). All in all, the bargaining power of suppliers has to be high, mainly due to the cost required to deliver on the chipmakers’ demands. However, with the participation of F450C, cost- and risk-sharing by G450C members, and an overall highly collaborative environment motivating new innovations, the effort is mutually beneficial to all parties.

Rivalry Among Competitors

Having a consortium creates a clear and definitive list of who is to be considered a competitor in this industry. In this case, though, none of these competitors are currently actively competing with each other on the 450mm front. One by one, each firm has announced withdrawal from immediate full commitment to the cause (Semiconductor Engineering, 2014). Each firm is still interested in 450mm technology becoming a reality, but none of them wants to be the first one to do it because whoever that is has to make the largest commitment to the R&D effort and cost. Whoever bears that cost may have the edge by being first out of the gate, but the firms all fear the possibility that the real competitive advantage comes to whoever goes second. The second firm can wait for the expense of R&D to be largely covered, then come make a considerably smaller investment to simply purchase the existing equipment and technology (Rahnama, 2015). Of course, that scenario is largely speculative, but “there is some level of mistrust [between these competitors], and there always has been,” and that’s probably what is slowing their decisions to move forward (Rahnama, 2015). Someone just needs to take the first step, and what follows is up in the air. The influence of rivalry among competitors only takes shape when more of the select few capable competitors join the fight, but once they do, that influence is quite high.

Weight of the Five Forces

In the early stages of 450mm conversion, there is a high threat of substitution if 450mm fabs cannot beat the cost of 300mm fabs, and the suppliers bargaining power is at its highest. After the initial conversion, buyer power begins to have strong influence, as does rivalry among competitors. At no point is there threat of new entry by firms outside of the G450C. So there it is, this is the field that competitors must enter if they choose to go forward with 450mm technology. However, so far all members of the G450C have basically halted activity. “Activity in a consortium is based on one thing:

resources. The two types of resources to consider here are human resources and money" (Rahnama, 2015). The one firm that seems to be willing to use the most of each of those two resources on 450mm technology is Intel. Is it worth it for Intel to invest those two resources on 450mm? Will they gain a competitive advantage by doing so?

Focus on Intel

Now that the above Porter analysis has set the context for the environment of 450mm technology, let us take now focus on Intel in particular and see if it is worth it for Intel to pursue 450mm technology. Up until recently, it appeared Intel was the only member of the G450C to be fully invested in the technology, however now they appear to be putting things on hold. Once again, Intel is faced with answering the central question: should they go forward, and how? Recall that we are considering four basic choices: 1) opt out 2) wait for another firm to go first 3) go first but run some fabs as 450mm and some as 300mm until 450mm becomes more cost effective or 4) go first and run full force at 450mm. The only strategy that offers a chance at a sustained competitive advantage is to fully adopt 450mm technology in all fabs as fast as possible. The sustained competitive advantage, however, comes from head start in the experience gained by the workforce, rather than from the technology itself.

Resource-Based View of the Firm

According to the Resource-Based View of the Firm, if a firm can exploit its strengths and neutralize its own weaknesses, then they maintain competitive advantage over their competitors. Ideally, they strive to create a sustained competitive advantage, which is one that is valuable, rare, hard to imitate, and hard to substitute. Intel's goal by making the 450mm conversion before anyone else is to turn it into a sustained competitive advantage. There are several ways that Intel could exploit a 450mm conversion to potentially create a sustained competitive advantage. First let us look at the technology itself and see whether or not sustained competitive advantage is inherent to the technology.

Value of 450mm Technology

What makes a fab running larger wafers more valuable is the ability to reduce the cost per unit area to generate the product. In figure 5B, the cost per unit area of 300mm wafers is shown to be 28% lower than that of 200mm wafers. If 450mm fabs can match that level of cost savings, then they will be more valuable than 300mm fabs. Along with the cost reduction, another high value element of size transition is the innovation that results from availability and continued development of new technology. As mentioned before, equipment suppliers are motivated to innovate when creating new tools. While some of their innovations can transcend technologies, the fact that they occur during 450mm equipment development improves the value of the 450mm infrastructure.

Rarity of 450mm Technology

By adopting 450mm technology before anyone else, Intel has a narrow window of opportunity during which 450mm is a rare asset. During that brief initial period of being the only firm with a 450mm fab, this resource is rare. However, once other firms start to open 450mm fabs, the rarity begins to dwindle. "Once the dam does break, the big companies will transition, and the reason for the transition is purely cost", which at that point is reduced by the fact that Intel fronts the initial R&D expenditures (Rahnama, 2015). There may still only be a small number of firms participating in the G450C consortium, but if they all run 450mm fabs then they do not exhibit the advantage of rarity over each other.

Non-Imitability of 450mm Technology

Similarly to the value of 450mm technology, non-imitability is defined by cost. Technically, 300mm fabs make the same thing that 450mm fabs will make, but they are differentiated by the cost that it takes to accomplish that task. Intel's goal is to make that differentiation in cost swing in favor of 450mm. In theory it does, but only once the 450mm fabs are up and running at full capacity. Once again, Figure 2 shows just how different the two types of fabs can be from one another.

Non-Substitutability of 450mm Technology

Obviously, 300mm fabs would be a substitute for 450mm fabs. This is, of course, only true if the cost of producing chips on 450mm fabs never goes down below that of 300mm fabs. Once again, Intel's goal is to make 450mm more cost effective than 300mm, so the assumption is that eventually this will be true. Until it is, though, 300mm fabs can definitely substitute for 450mm fabs.

Is 450mm Technology a Sustained Competitive Advantage?

If Intel is the first to build a 450mm fab, the technology creates competitive advantage for Intel in some form or another at all points in time. However, these advantages are all transient. Based on cost, the advantages of value, non-imitability, and non-substitutability only occur after the technology has matured to the point where it costs less to generate a chip in a 450mm fab than it does in a 300mm fab. The rarity of an Intel-operated 450mm fab goes away as more firms build their own 450mm fabs. Rarity of the innovations that go into 450mm technologies also go away as suppliers choose to integrate those ideas into their new 300mm products. In truth, 450mm technology is not inherently a sustained competitive advantage. The resource that is, though, is the leading edge that the employee workforce gains by being years ahead of the competition.

Value of Experienced Employee Workforce

Let us assume that Intel builds a 450mm fab 5 years before the next member of the G450C. By the time that second firm first opens the doors to their new fab, Intel's employees will have had 5 years' worth of experience with the technology. It is also important to consider the technology node of the products that are being made at that point in time. "Intel will never go into a new process technology node with a new wafer size. Intel will always repeat the current technology node with the new wafer size, they will go sideways. Once you show capability and matching, at that point you are certifying that 450mm is a viable size node" (Rahnama, 2015). This is a necessary step that each firm will have to undergo, and their workforce will have to experience that learning curve. Intel's employees will already have made the horizontal transition of copying a process node from 300mm to 450mm technology, plus by then they likely would have begun on a brand new process node unique to 450mm. The value of having that experience and that head start is very high.

Rarity of Experienced Employee Workforce

Obviously, if the only people in the world who have that extra 5-or-so years of experience are Intel's employees, they will always be the only workforce with that much more experience. That is not to say that other firms' employees are incompetent, just that they will never have as much experience with 450mm equipment and infrastructure as Intel's employees. They also would never have gone through the same frustrating challenges of technology in its true infancy, which teaches lessons that cannot be substituted by any other type of experience.

Non-Imitability of Experienced Employee Workforce

While other firms can purchase the same 450mm tools and technology that Intel utilizes, which they certainly will, there are elements of the infrastructure that are generated in-house by each firm. One example of this is automation. Instrumentation for tools of a given wafer size is designed to be compatible with one another, which is largely the point of having a uniform wafer size. Although tools are all compatible, automation software is a part of a fab's infrastructure that is not standardized across the industry. Each firm must develop their own automation software and, in part, hardware. For 300mm technology, for example, TSMC is known to have some of the best automation software in the business. The operations that take Intel several hours to put together can take minutes for TSMC to set up (Rahnama, 2015). The 450mm transition needs to be a "revolutionary change, not an evolutionary change," meaning factors like the current system of automation will need to be altogether redesigned to accommodate new criteria (Rahnama, 2015). Whatever Intel's automation workforce comes up with will be unique to Intel, and it will have a head start over other firms by coming first.

Non-Substitutability of Experienced Employee Workforce

A competing firm could certainly hire new employees from top universities or with superior background work experience. Arguably, this could be considered a substitute of an altogether different resource. However, they will not be able to outfit their workforce with a head start on 450mm technology, not unless they hired exclusively former Intel employees. Unless they can accomplish the same results as Intel's workforce by some other means, specifically that they can catch up to the same transistor node as Intel, then Intel maintains a competitive advantage (Barney, 1991). It is also important to note that members of the firm's workforce tend to be specialists. "Everyone has a specific job, a specific task that they focus on and care about," and the amount of time that it takes to achieve expertise in that specialty is not substitutable (Ma, 2015). Everyone has to put in the work to iron out the challenges, both as individual specialists and as an organization.

Is an Experienced Employee Workforce a Sustained Competitive Advantage?

An Intel workforce with a head start on experience utilizing brand new 450mm technology is certainly valuable, it will remain rare for a long time before other firms' employees catch up to such a level of experience, it is unique to Intel's workforce and not imitable, and it is not substitutable because competitors will not be able to catch up to the same product transistor node at the same time or cost as Intel. Therefore, an employee workforce with a head start on experience with 450mm technology is a sustained competitive advantage. It would be worth Intel's investment to pursue outfitting of all of its fabs with 450mm technology as soon as possible based on the sustained competitive advantage that it would gain by having a more experienced workforce. Investing in getting its entire workforce familiar with 450mm technology ahead of the competition will ensure that all fabs owned by the corporation have a leading edge over any 450mm fabs built by competitors.

Lessons Learned In Previous Transitions

Previous transitions offer some insight on sorts of challenges Intel's workforce faces by transitioning to a new wafer size. As individual employees, everyone is bound to encounter unexpected problems within their own small piece of the puzzle, but that is a given (Ma, 2015). What people may not be able to foresee is the impact of one module's problems on the rest of the members of the fab. For example, with the previous transition, the 200mm wafers were transferred by cassette in a hand-carry fashion, but for 300mm wafers that was not possible due to their weight and size. The solution was to create an automation system with overhead tracks to move FOUPs from loadport to loadport. This was not a seamless transition. Automation was full of bugs and coding issues. There was a long period of time where personal-guided vehicle (PGV) carts were used while the automation group was working out their hardware and software problems. Traffic on the fab floor was high, progress was slow, and it was a frustrating environment (Hwang, 2015). However, everyone had to play their part, so everyone had to trust the automation group to solve the issues at hand. Today, automation in Intel's fabs runs very well, but it certainly had a learning curve that everyone in the fab had to experience.

Tool selection was another element of previous wafer size transition with unique challenges. Once again, most people had to trust that the individuals making the decisions could deliver the best results. One thing that Intel does exceedingly well is preceding all decisions with mountains of data and statistical analyses (Hwang, 2015). In a tool selection scenario, a process engineer would need to establish selection criteria, so they would set out in a team to collect data for the individual selecting the tool to form the basis of their decision. "Everyone kind of improvises because everything was under construction," but this environment encourages teamwork and innovation, further increasing the value of the experience for the workforce as a resource (Hwang, 2015).

The biggest challenge in the past has been infrastructure (Hwang, 2015). It is hard to predict precisely what a 450mm fab will look like. There are individuals whose jobs it is to predict what some of the limitations are going to be. For example, if the 450mm wafers are going to be transported via overhead delivery systems, as they are in 300mm fabs, then someone at Intel must coordinate with vendors to envision how that will function. Will the same number of wafers be loaded into each FOUP? What will the volume of the overhead delivery path need to be, and how will that impact the size of the fab? What about cleanliness? In the past, Intel's fabs were Class 1, but many can now be Class 10 or 100. In the previous wafer sizes, wafers were transferred in cassettes and with wafer wands, but the introduction of the FOUP system allowed wafers to be transferred from one sub-Class 1 tool microenvironment to another sub-Class 1 tool microenvironment without ever being exposed to outside air. 300mm fabs can also avoid the bay-and-chase structure of 200mm fabs and opt now for ballrooms, which allow more flexibility (Rahnama, 2015). It's hard to imagine how moving to 450mm tools might change further still, but it could continue to evolve and the workforce will have to adapt and continue to innovate with the changing circumstances.

Many unforeseeable issues may occur as a result of increasing wafer sizes. One thing that is certain is that some modules must take priority over others in the initial stages. Metrology tools, sort/die prep, and E-test should be the first priorities (Rahnama, 2015). In order to develop a process on a technology node, feedback loops are essential and "if you don't have them then you're dead in the water" (Rahnama, 2015). This makes the bargaining power of suppliers of those types of tools very high, but once again it is beneficial to everyone to motivate innovation with the prospect of 450mm technology. For example, KLA-Tencor released a Surfscan® SP3 450 in 2012, a metrology tool designed for 450mm wafers, but capable of inspecting both 300mm and 450mm wafers at the 20nm node (KLA-Tencor, 2012).

Conclusion

It is quite an expensive bet to convert all of the firm's fabs into 450mm facilities, but it really is the best option for Intel. Now it is a question of when Intel will act. Moving forward on a big change like this one is like overcoming activation energy. The decision to move forward, though, is "entirely a cost based decision, not a technology based one" (Ma, 2015). Intel should take that bet, though, and reap the benefits of a workforce with more experience than anyone else in the industry. This will create a sustained competitive advantage and will pay off when other firms decide to join the 450mm ecosystem.

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