Mask Cost and Profitability in Photomask Manufacturing: An Empirical Analysis

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Abstract – *An empirical study of the economics of manufacturing photomasks concludes that the uncontrolled growth of optical proximity effect correction and resolution enhancement techniques is driving up the cost of pattern generation and mask inspection to levels that threaten the profitability of photomask manufacturing. The intrinsic cost of some leading edge photomasks has already exceeded the price that customers are willing to pay for them. A model of the lifecycle of photomask manufacturing, developed from interviews involving the 1990 to 2005 operations of six mask shops and a survey of seven photomask manufacturers, shows that design for manufacturability (DFM) constitutes the most promising approach for alleviating this market impasse. Unilateral action by mask shops to increase their capital productivity is necessary but insufficient and perhaps unaffordable. DFM solutions will require the majority of participants in the lithography value chain to collaborate according to a volatile demand schedule that is driven by semiconductor manufacturers.*

Keywords: Mask, Costs, Profitability, Photomask, Manufacturing

I. INTRODUCTION

For the past four decades, Moore's Law [1], which states that the number of transistors that can be built into a given amount of chip space will double every 12 to 18 months, has been driving the dimensions of merit for semiconductor manufacturing and its enabling technologies. Foremost among these enabling technologies is optical projection lithography, which faces the particularly daunting challenge of resolving integrated circuit features whose dimensions shrink by 30% every two to three years [2], [3]. In optical projection lithography, the resolution W of a lens at the diffraction limit is given by the Rayleigh criterion

$$W = k_1 (\lambda / NA), \qquad (1)$$

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where λ and NA, respectively, denote the wavelength and numerical aperture of the exposure tool, and k_1 is an empirical constant affected by numerous elements including lens aberrations, illumination conditions, resist contrast, etch quality, and photomask enhancements [4]. Smaller feature sizes can consequently be resolved by choosing a light source with a shorter wavelength, by increasing NA, or by reducing k_1.

Light sources with progressively shorter wavelengths and lenses with higher numerical apertures have been successfully embodied in lithographic projection tools over time, but these efforts have not kept pace with the requirements of Moore's Law. Efforts to reduce k_1 have therefore been underway since minimum feature sizes first shrank below 0.5 μm. Optical proximity effect correction (OPC) and resolution enhancement techniques (RETs) such phase shift masks (PSMs) and off-axis illumination (OAI) have been introduced to keep W on the Moore's Law trajectory. They have pushed optical projection lithography into the "sub-wavelength" domain, where lithographic projection tools are able to print features that are significantly smaller than the wavelength of the light source. [3], [5]

OPC and PSM have driven up the complexity of photomasks beyond what could be expected from Moore's law, and the cost of producing photomasks has been rising accordingly. OPC in particular introduces ultra-small sub-resolution features into a mask, which compensate for how light modifies a mask pattern when it reaches the wafer. These extra features dramatically increase the data size associated with a mask, driving up the time required to write and inspect the mask [5]. Phase shift masks enhance contrast to expose the photoresist and print features at resolutions that cannot be achieved with conventional binary masks (for any particular commercially available combination of λ and NA). However, when compared to binary masks, PSMs require more sophisticated and expensive starting material (mask blanks) [6], [7], and the process for producing PSMs is more complex and more costly [8].

The proportion of masks within a mask set that incorporate OPC and phase-shift technology is rising as the minimum IC feature sizes continue to shrink [3], [9]. As a consequence, the cost of a mask set is expected to increase from ~US$ 500k for the 130 nm technology node to ~US$ 1 million for the 90 nm node and to ~US$ 2 million for the 65 nm node [8]–[14]. In addition, it has been suggested that the leading-edge layers are the primary drivers of the cost of a mask set. Contact-1 and via-1, which tend to be PSMs, as well as poly/gate and active, which tend to exhibit the highest feature density, generally lead the pack. Metal-1 and metal-2 follow not far behind [8].

Previous analyses of the economic aspects of photomask manufacturing (e.g., [8], [11], [15]-[18]) have not focused on how the economic conditions faced by semiconductor manufacturers affect the ability of photomask manufacturers to make a profit. Semiconductor manufacturers are under time-to-market pressure and time-to-volume pressure because the prices for most semiconductor products fall over time [19]-[21]. Semiconductor manufacturers try to improve yield and increase output as soon and as rapidly as possible to achieve volume production while the price for their products is still high [19]-[22]. The chipmakers' demand for photomasks is thus likely to vary over time, and the mask maker has to make investment decisions that are in accord with this varying demand. The impact of these decisions on mask cost and the profitability of photomask manufacturing has yet to be characterized in detail.

In this paper, we conduct a study of the economics of photomask manufacturing that incorporates some of the dynamics of semiconductor manufacturing. Our research question is, "What are the mechanisms that enable and/or limit profitability in photomask manufacturing?" Using qualitative research methods that are described in section II, we identify variables that serve as candidates for drivers of profitability in photomask manufacturing (section III), and we develop an analytical financial model that tracks the candidate variables throughout the photomask manufacturing lifecycle. In section IV, we customize this model to the production of leading-edge photomasks. In section V, we conduct a sensitivity analysis of the candidate variables to assess their impact on the profitability of photomask manufacturing. In section VI, we discuss how various industry practices affect profitability in photomask manufacturing and semiconductor manufacturing. We summarize our conclusions in section VII.

II. RESEARCH METHODS

The findings of this study are based upon the case study research method [23], [24], a qualitative approach that has been implemented successfully in previous studies of the semiconductor industry [20], [25]. This method was chosen because photomask manufacturers and semiconductor manufacturers are highly reluctant to make quantitative technical data and financial data available to outsiders. Case study research also permits inferences from multiple sources [24], e.g., interviews and surveys. It is particularly useful for generating analytical models of complex economic and social processes. However, models generated from case study research are derived from data samples that are purposely biased to reveal the mechanisms that govern the processes under study. Consequently, conclusions derived from these models do not carry statistical significance [23].

The unit of analysis of the study is the relationship between the manufacturers of photomasks and their customers, the semiconductor manufacturers. The cases under investigation transpired in six mask shops between 1990 and 2005. Some of these mask shops were owned by merchants, and some were captive. The lifecycle of a particular technology node (e.g., 180 nm, 130 nm, 90 nm, 65 nm) constitutes a case. Four advanced technology nodes—180 nm, 130 nm, 90 nm and 65 nm—were investigated in three mask shops. Less advanced technology nodes (250 nm and above) were investigated in four mask shops. They are considered a base case.

Thirteen respondents who were personally involved in the cases recounted them in personal, one-on-one interviews. Seven respondents recounted the photomask shop manufacturers' perspective. Six reported from the point of view of a customer. The respondents answered specific questions concerning photomask-related technical and financial variables In particular, respondents were asked to explain how the numerical values of these variables evolved over time. In addition, respondents were asked open-ended questions, the answers to which provided a more detailed explanation of why the variables in each case varied over time as they did. A detailed list of the interview questions is in [26].

As recommended in [25] and [27], data from the above case interviews have been compared to data from secondary sources to avoid undesired confusion between the unit of data collection (individuals) and the unit of analysis (the relationship between photomask manufacturers and their customers). Secondary sources include past editions of SEMATECH's annual survey of photomask manufacturers [12]-[14] and projections of technical trends that have been printed in the 2003 edition of the Semiconductor Industry Association's *International Technology Roadmap for Semiconductor*s [28]. In addition, 79 productivity-oriented questions were attached to SEMATECH's 2005 Mask Industry Assessment survey of photomask manufacturers to supplement its traditional technical questions. Fifteen of the supplementary questions elicited information regarding mask shop operating cost factors; the remaining 64 questions pertained to equipment utilization. (See [26] for a detailed list of the productivity-oriented questions.) The productivity-oriented questions were answered to a large degree by seven major global merchant and captive mask manufacturers whose combined revenue represented more than 75% of the global mask market in 2005.

Theoretical saturation, a state of affairs in which the replication of cases would yield diminishing returns [23], [24], was achieved relatively easily. Analysis of data from within individual cases revealed consistent patterns illustrating how technical and financial variables evolved over time within a particular technology node. Comparing cases (cross-case analysis) provided insight into changes that occur from technology node to technology node and suggested a few candidate variables that potentially drive profitability in photomask manufacturing (section III). Analysis of data from secondary sources confirmed the conclusions derived from within-case and cross-case analyses.

An analytical model of the photomask manufacturing lifecycle has been derived from within-case analysis, cross-case analysis, and analysis of the data from secondary sources. The model tracks key technical and financial variables throughout the lifecycle of a photomask manufacturing process, from the early stages of process research through mature volume production. These variables can be customized to explain the internal mechanisms of manufacturing masks of different levels of complexity. The model is calibrated such that t=0 represents the inception of a semiconductor venture, the point in time at which simulation activity of semiconductor devices and products begins for a particular technology node. This point in time roughly corresponds to the time a photomask manufacturer makes key decisions about capital outlays that pertain to a particular technology node.

Key aspects of the model of the photomask lifecycle have been validated in interviews with 25 experts in photomask manufacturing, photolithography, VLSI circuit manufacturing, VLSI circuit process development, tool development, materials development, and related technical fields. These experts were recruited by recommendations from within their respective peer groups. In addition, some of the respondents that recited a case have acted as validation experts for cases other than their own. The technical complexity of photomask manufacturing and process development, as well as semiconductor manufacturing and process development, has warranted such a large number of expert interviews. For example, an expert in materials engineering would not necessarily be able to validate the relevance of a case that revolved around optics and polymer chemistry. Similarly, aspects of a case in which production management skills were germane to performance improvement required validation by experts in operations management, logistics, or supply chain management, rather than validation by technical experts.

III. CANDIDATE VARIABLES

In this section, we discuss key findings of the study described in section II for which theoretical saturation has been achieved. These findings allow us to decompose the cost structure of the photomask production process into variables that potentially dominate the cost of mask making. We identify these variables, as well as the quantity of photomasks demanded per unit time ‘Q(t)’ and the average unit sales price of photomasks ‘P(t)’, as candidates for drivers of profitability in photomask manufacturing.

According to our respondents, as well as [8], pattern generation (PG) accounts for about 35% of mask costs; mask inspection and QA account for about 40%. The rest of the production process (primarily development and etch) contributes about 10%. These costs are primarily fixed; they depend upon the utilization of highly expensive capital equipment. The remaining 15% of mask costs are attributed to the cost of materials, which is primarily variable and dominated by the cost of starting material (mask blanks).

Table 1 illustrates that the respondents in this study associate the price of masks with the cost of the tools on which they are written and inspected, as well as the throughput that can be effectively achieved on these tools. Our respondents identify three distinct classes: A, B, and C. Masks of class A contain no OPC; they can be written on laser-based PG tools, which can be purchased for about US$ 7 million each; and they can be inspected on tools that are not state of the art. Thus they can be written and inspected at a relatively high throughput and with relatively low costs. Masks of class B can also be written on laser-based PG tools and inspected on tools that are not state of the art, but they do contain OPC, which increases the likelihood of multiple inspections per mask. Their inspection times are significantly longer, driving down the throughput that can be achieved on inspection tools. The price of class B masks rises accordingly. Requirements for capital investment rise dramatically for class C masks, which are written on vector scan electron beam (VSEB) tools that cost US$ 15 million [7] or more. According to our respondents, the increasing prevalence of model-based OPC (MBOPC) and phase shift masks is causing total inspection time per mask to increase more rapidly than PG time per mask. For example, for class C masks, as many as two inspection tools with a price tag of around US$ 20 million each need to be purchased to evaluate the output of one VSEB PG tool. The price of class C masks is rising accordingly to levels that the buyers of such masks are reluctant to pay.

{Insert table 1 and table 2 about here.}

The cost structure that underlies Table 1 suggests that the profitability of mask making could be driven by the marginal cost of production capacity, which is defined as the capital investment that is required to produce one additional mask within a specified time interval, Δt. The marginal cost of production capacity of a mask shop is given by

$$mc_{pc}(t) = c_{equ} / T(t) = c_{equ} / [T_{max} U(t)], \qquad (2)$$

where c_{equ} gives the cost of the capital equipment that is required to achieve a desired throughput T(t) for a mask shop that produces a particular mix of masks. T(t) can be decomposed multiplicatively into T_{max}, which denotes the theoretical maximum intrinsic throughput of the tool set, given the particular mix of masks, and U(t), an indicator of how well the mask shop utilizes capital equipment.

A significant number of mask shops in our sample estimate the mask shop's utilization of capital in terms of the yield rate

$$U(t) = Y_{up}(t) Y_{ru}(t) Y_{pp}(t) Y_{ln}(t) Y_{nr}(t), \qquad (3)$$

where $Y_{up}(t)$ is the fraction of time that capital equipment is not undergoing scheduled or unscheduled maintenance; $Y_{ru}(t)$ is the fraction of time available equipment is actually running; $Y_{pp}(t)$ represents the proportion of plates running are production plates; $Y_{ln}(t)$ is the fraction of production plates that are not scrapped during the manufacturing process; and $Y_{nr}(t)$ denotes the fraction of non-scrapped production plates that are not reworked. (This definition is consistent with operations research approaches to waste reduction that are described in [29]-[32].) All variables in equation (3) are functions of t, which are expected to saturate at levels below unity during volume production.

Judging from the results of the 2005 Mask Industry Assessment survey [14] and comments given by the respondents in this study, the values for the constituent factors to capital utilization during volume production can be estimated somewhat optimistically as $Y_{up}(t) = 0.9$; $Y_{ru}(t) = 0.95$; $Y_{pp}(t) = 0.9$; $Y_{ln}(t) = 0.9$; and $Y_{nr}(t) = 0.95$. Substituting these values into equation (1) gives $U(t) = 0.66$, which indicates at least one-third of all resources in photomask manufacturing are wasted. The causes of this waste have been analyzed successfully over the years [12]-[14].

Table 2 exhibits estimates of mc_{pc} for masks of all three classes that are based upon inputs from respondents. Column 1 shows the assumed write time for a mask of each class. Column 4 indicates the number of masks one PG tool can write in 90 days (Δt = one quarter), assuming the PG times per mask from column 1 and a capital utilization rate of 0.66 (column 3). Column 5 contains estimates of the US$ equivalent in capital equipment (PG tools, inspection tools, etchers, developers, etc.) that is required to achieve the throughput numbers from column 4. The figures from column 5 are divided by those from column 4 to estimate the capital investment required to produce one additional mask every 90 days. This number, which is displayed in column 6, increases dramatically from mask class to mask class.

In addition to marginal cost of production capacity, we propose that the following variables could affect profitability in photomask manufacturing significantly. First, we suggest that an increase in materials costs, which is expected as phase shift masks become more common [3], [9], could cause profit margins to erode. Second, we shall assume that $P(t)$ is driven by market forces rather than mask cost. Photomask manufacturers must consequently adapt to changes in $P(t)$ to remain profitable. Finally, we submit that photomask manufacturers base their capital investment decisions on $Q(t)$, a variable that is driven by the needs of chipmakers and fluctuates over time.

IV. THE PHOTOMASK PRODUCTION LIFECYCLE

Our respondents consistently indicate that economic models of photomask manufacturing, if they are to be accurate, must take into account that key financial and managerial variables vary substantially over the lifecycle of a particular mask class. The analytical model presented in this paper consequently tracks all the abovementioned candidate variables for profitability throughout the photomask manufacturing lifecycle. Three high level financial variables have been added: the mask maker's revenue generation rate, $R(t)$, the cash outlay rate, $C(t)$, and the profit generation rate before taxes, $\Pi(t)$. The model can also be customized to different product mixes.

{Insert figure 1 about here.}

Figure 1 depicts the lifecycle of a manufacturing process at a hypothetical photomask manufacturer that produces nothing but class C masks, which constitute the leading edge of the 130 nm technology node. Figure 1 tracks the behavior of Q(t), P(t), R(t), C(t), and Π(t) from t=0, the point of inception of the 130 nm technology node (whose calendar dates vary from chipmaker to chipmaker) to maturity. In Figure 1, Q(t) is given in thousands of masks per quarter; P(t) is given in hundreds of thousands of nominal US dollars per unit; C(t) and Π(t) are given in hundreds of millions of nominal US dollars per quarter. For the purpose of clarity in Figure 1, R(t) is given in units of nominal US$ 50 million. A score of 1.0 for R(t) in Figure 1 would therefore imply that revenue of a nominal US$ 50 million has been generated in a 90-day period.

According to the respondents in this study, Q(t) for class C masks varies significantly over the photomask production lifecycle. The first demand spike for a leading photomask occurs around t=1 year, when the majority of chipmakers need a test mask set to characterize their tools and processes for the 130 nm technology node. Another demand spike occurs around t=2.5 years, when leading-edge chipmakers require a mask set that acts as a vehicle for yield improvement. The leading-edge class C masks in these mask sets are called *early masks* because they are needed while the next-generation semiconductor process is still under development. The demand spikes generated by early masks are minor, yet photomask manufacturers are inclined to meet them. Learning along with leading-edge semiconductor manufacturers increases the chances of obtaining downstream business when chipmakers ramp to volume production.

Semiconductor manufacturers tend to ramp the new technology node up to volume production around t=4 years. Consequently, the supplying photomask manufacturer must possess the capability to generate *production masks* in large quantities before that date, typically around t=3.5 years. Semiconductor manufacturers tend to introduce many new designs into manufacturing between t=3.5 years and t=5 years, generating peak demand, Q_{pk}, for masks during that time interval. For example, Q(t) in Figure 1 rises to a level of Q_{pk}=1000 class C masks per quarter, which is consistent with the introduction of about 1500 new 130 nm designs between t=3.5 and t=5 years. Q_{pk} dwarfs the previous demand for early masks, which is barely detectable in Figure 1. The demand for leading-edge masks decays exponentially by about 5% per quarter after t=5, when the majority of new designs have been introduced and new business primarily comes from replacement masks and derivatives of existing designs.

According to our respondents, the nominal unit sales price, P(t), for new masks decays exponentially, dropping by a factor of two about every three years. For example, respondents consistently report that the average unit sales price of early masks is about twice as high as the price obtained during peak demand (3.5 years < t < 5 years). P(t) is consequently modeled as

$$P(t) = P_0\, 2^{-t/3}, \tag{4}$$

where the constant P_0 denotes P(t) at t=0. This price evolution is the result of negotiations between chipmakers and mask makers, which occur within the context of a joint lithography roadmap. A manager responsible for mask procurement at an ASIC manufacturer explains:

> "There is lots of room for improvement in the mask-making process.…Improved process quality would increase the mask shops' yields and profit margin.…If we help them, then they can pass some of that [profit] on to us.…We are willing to pay more for a mask that enables our R&D effort. However, prices must come down when we go into production so that we can remain competitive."

In Figure 1, P_0 = US$ 100k, which reflects the respondents' expectations for sophisticated class C masks. Figure 1 suggests that an early class C mask can be sold for about US$ 80k at t=1 year; a production mask for about US$ 40k at t=4 years; and a mature mask for about US$ 20k at t=7 years.

The revenue generation rate R(t) is defined as the multiplicative product of P(t) and the rate at which photomasks are produced at time t. If we assume that mask makers produce to the quantity demanded, then we can state that R(t) = P(t) Q(t). R(t) is a volatile function of t, which is constrained by its constituent factors. Before t=3.5 years, when P(t) is high, R(t) is limited by the small demand for early masks. After the surge in demand that occurs at t=3.5 years, R(t) erodes as P(t) decays exponentially.

The cash outlay rate C(t) is defined as the nominal amount of cash that is paid out per unit time (e.g., a quarter). C(t) can be decomposed additively into constituent cash outlay rates for personnel, materials, miscellaneous expenses, and capital investment. The findings of our study suggest that during photomask R&D (t < 3.5 years), the cash outlay rates for personnel, materials, and miscellaneous expenses constitute a steady stream of expenses. Accordingly, the mask maker in Figure 1 assumes that 50 technologists, costing an average of $160k per year each, are involved full time in developing a process for fabricating class C masks. These personnel costs amount to US$ 2 million per quarter. Materials costs and miscellaneous costs generate an additional US$ 500k of expenses per quarter during process development, bringing the total to US$ 2.5 million per quarter. During volume production ($t \geq 3.5$ years), materials costs and miscellaneous costs are assumed to amount to US$ 5000 per mask; personnel cost are included in estimates for investment in production capacity and do not need to be treated separately.

The cash outlays for capital investment tend to manifest themselves as punctuated surges that respond to changes in Q(t). For example, the mask maker in Figure 1 anticipates that a modicum of demand for early class C masks will materialize around t=1 year. The mask maker consequently decides to invest US$ 50 million in technology (primarily PG and inspection equipment) at t=0, which he/she pays off over the next four quarters. (In general, photomask manufacturers pay their equipment suppliers according to four milestones: order, physical installation, up and running, and final acceptance. These events are assumed to occur three months apart, and payments for each of these milestones are assumed to be the same [26].) This investment enables the mask shop to produce up to 240 masks per quarter. No major additional investments are needed between t=1 year and t=3 years, a time when the demand for class C masks is low.

C(t) rises to it highest level when the mask maker purchases capital equipment to meet the surge in demand that is anticipated for between t=3.5 years and t=5 years. The mask maker in Figure 1 expects to produce 1000 class C masks per quarter during this time period. If that mask maker follows the analysis given in Table 2, then he/she will require a total of US$ 208 million of capital equipment to achieve this product output rate. The initial US$ 50 million in capital equipment, which has been purchased at t=0, can be subtracted from this sum, if said equipment can still be utilized. We can thus assume that the mask maker in Figure 1 will purchase US$168 million that he/she will pay in four equal and equally spaced installments from t=3 years to t=4 years.

According to our respondents, this surge in capital investment suffices to cover the expected demand for class C masks for $t > 4$ years, primarily because $Q(t)$ drops when $t > 5$ years. However, capital utilization must remain constant when $t > 5$ years for marginal cost of capacity not to rise. Consequently, the mask maker in Figure 1 has to rely on demand for class C masks to come from more advanced technology nodes (e.g., 90 nm, 65 nm), if the capital utilization rate of the mask shop is to remain equal to 0.66 when $t > 5$ years.

The nominal profit generation rate before taxes, $\Pi(t)$, is defined as the difference between the nominal revenue generation rate, $R(t)$, and the nominal cash outlay rate, $C(t)$. Figure 1 shows that $\Pi(t)$ remains negative throughout the early stages of the photomask production lifecycle. The ramp to volume production at $t=3.5$ years generates a surge in $\Pi(t)$ that significantly exceeds the magnitude of the peak cash outlay rate. However, $\Pi(t)$ erodes over time as the unit sales price, $P(t)$, and quantity demanded, $Q(t)$, decay exponentially over time.

V. SENSITIVITY ANALYSIS

To determine the profit potential and breakeven point of class C masks, we calculate the net present value, $NPV(t)$, of the assumptions that underlie Figure 1. This calculation constitutes the base case of a sensitivity analysis in which the variables with ability to affect mask shop profitability are varied, ceteris paribus (i.e., all other variables and parameters are kept constant):

$$NPV(t) = \int_0^{\tau} \{[P(t)\, Q(t) - C(t)]/(1+\kappa)\}\, e^{-t}\, dt, \qquad (5)$$

where τ represents the investment horizon (e.g., ~ 10 years for a photomask venture), and κ denotes the opportunity cost of capital [33], which, according to our respondents, typically amounts to about 15% per year for photomask manufacturing. $P(t)$, $Q(t)$, and $C(t)$ behave as shown in Figure 1. The results of these calculations indicate that breakeven occurs around $t=6.5$ years and that US$ 24.7 million of real profit before taxes can be made over a photomask manufacturing lifecycle that lasts until $t=10$ years. According to the general consensus among our respondents, this estimate is somewhat optimistic but fundamentally achievable. Given that the assumptions of the model of the photomask manufacturing lifecycle are based on what surveys of photomask manufacturers [12]-[14], [26] suggest the best in the industry are achieving, such a consensus opinion is to be expected.

Figure 2 displays Q(t) for a sensitivity analysis in which the peak quantity demanded, Q_{pk}, is varied from 500 masks per quarter to 2000 masks per quarter, ceteris paribus. The assumptions for capital outlay are scaled in accordance with Q_{pk}. Investment in capital equipment increases by US$ 208k for every mask per quarter of capacity above the first 240 masks per quarter. This investment is paid over four quarters between t=3 years and t=4 years. All the other assumptions carry forward from the base case. Q(t) decays by 5% per quarter after t=5 years; the assumptions for P(t) do not change from Figure 1; U(t) is assumed to equal 0.66; and materials costs amount to $5000 per production mask.

The results of the sensitivity analysis, which are displayed in Figure 3 and Table 4, illustrate that profitability is a strong function of scale. Even with an optimistic capital utilization rate of U(t>3.5 years) = 0.66, NPV(t) remains negative for all t unless the peak quantity demanded (and produced) exceeds 640 masks per quarter. Above that peak level of Q_{pk}, breakeven shifts forward in time, and NPV(t=10 years) moves upward as a function of Q_{pk}. If the peak quantity demanded equals 2000 masks per quarter, then breakeven occurs at t=5.6 years and NPV(t=10 years) = US$ 91 million. However, taking advantage of scale is contingent upon the ability to invest heavily in capacity. For example, Figure 2 illustrates that a peak production capacity of 2000 class C masks per quarter requires a cumulative net cash outlay of US$ 210 million before volume production.

{Insert figure 2, figure 3, table 3, table 4, table 5 and table 6 about here.}

Tables 4, 5, and 6, respectively, illustrate the consequences of varying average unit sales price, materials cost and marginal cost of production capacity, ceteris paribus. (P(t) is varied in a manner in which only P_0 increases or decreases; the rate of decay remains unchanged at $2^{-t/3}$. See equation (4).) The results of all three sensitivity analyses indicate that NPV(t=10 years) is a nearly linear function of P_0 and a nearly inverse linear function of materials cost and marginal cost of capacity. Ceteris paribus, for a mask shop that manufactures class C masks to remain profitable, the price of such masks in volume production (t=4 years) cannot go below US$ 36k; the materials cost required to produce such masks cannot exceed US$ 8000 per mask; and the marginal cost of production capacity cannot rise above US$ 245k per mask per quarter.

VI. DISCUSSION OF PRACTICES

The sensitivity analysis from the previous section suggests that the ability to manufacture class C masks profitably is precarious at best. The ability to make a profit in manufacturing leading-edge photomasks is highly sensitive to scale, to materials cost, to unit sales price, and to the ability to add production capacity according to a volatile demand schedule. The profitability potential of photomask manufacturing could therefore increase in any of the following ways: through an augmentation in production capacity, through an increase in what the buyers of leading-edge photomasks are willing to pay for masks, through a decrease in materials costs, and through a reduction in marginal cost of production capacity mc_{pc}. According to equation (3), mc_{pc} can be reduced in three ways: 1) by lowering the cost of capital equipment c_{equ}, 2) by increasing capital utilization U(t), or 3) by increasing the maximum intrinsic throughput of capital equipment T_{max}.

Our respondents clearly indicate that the cost of producing leading-edge photomasks is increasing more rapidly than the buyers' willingness to pay. Masks whose PG times are approaching 24 hours and whose total time spent on inspection tools exceeds 24 hours can no longer be sold profitably. They cannot be produced for less than US$ 150k, which exceeds what buyers are willing to pay for them. Mask makers consequently sell these masks at or below cost as part of a mask set. They recover the incurred losses by selling the remaining masks within the set (class A masks, class B masks, and class C masks with relatively short PG- and inspection times) at a profit. Given that the share of more complex masks within a set is increasing as minimum feature sizes shrink [3], [9], this practice appears economically unsustainable in the long run.

Materials costs for high end masks are not likely to decrease because the cost of the starting material (mask blanks) is going up as more sophisticated production technologies are being introduced. Prices of US$ 4000 have been suggested for mask blanks from which sophisticated PSMs are being realized [6], [7]. Thus a major increase in mask shop profitability is not likely to come from a reduction in materials costs. However, respondents employed by semiconductor manufacturers have indicated that materials costs could be absorbed into the costs of producing leading-edge chips, as long as these costs amount to less than 20% of the total cost of a mask.

According to respondents employed by tool suppliers, a reduction in the cost of capital equipment c_{equ} is very unlikely in the next five years. Manufacturers of PG tools and inspection tools, in particular, believe that they have to make significant investments in technology development as long as the pattern density and complexity of photomasks continue to increase. To reduce the unit price of tools and still remain profitable, tool suppliers have to recover the costs of making the tools by selling many tools to photomask manufacturers, an unlikely prospect in an industry whose total annual revenue tends not to exceed US$ 3 billion [12]. An engineering manager at a leading maker of PG tools explains:

> "We consider a product line successful if we sell more than 100 tools. We are not likely to sell 100 [PG tools] to the mask makers in the next few years. …Even if we leverage technologies from some of our other product lines, we have to charge high prices to continue this product line."

Capital utilization can be improved by engaging in practices that increase all the constituent yield rates of U(t) that are given in equation (3). These include increasing equipment uptime and availability, reducing the number of engineering plates, improving yield through the reduction of hard defects, and reducing the rework rate. Many of these practices involve significant engineering efforts and possibly substantial investments in factory automation. Since profitability is a function of scale, large photomask manufacturers are more likely to be able to afford these efforts and investments. For example, the mask maker in Figure 3 that produces to a Q_{pk} of 2000 masks of class C per quarter harvests US$ 91.2 million, which he/she can invest in automation or engineering personnel, whereas a mask shop that produces to a peak demand around 700 class C masks per quarter would have very little to reinvest.

The multiplicative nature of equations (2) and (3) suggests that the impact of improving capital utilization is likely to be nonlinear. U(t) is likely to remain low until all factors in equation (3) contributing to capital utilization exceed 0.7. At that point, capital utilization will rise dramatically and the marginal cost of production capacity will fall significantly. However, U(t) saturates once all its constituent factors approach unity, and continuous improvement in capital utilization reaches diminishing returns.

An increase in the maximum intrinsic throughput rate of a mask T_{max} for leading-edge masks is likely to come from design for manufacturability (DFM), the general designation for a variety of ongoing efforts that have the potential to reduce the pattern complexity of photomasks without inducing quality problems in mask making or semiconductor manufacturing. DFM efforts include reducing OPC complexity by relaxing over-specified feature requirements [9]; developing OPC segmentation technologies that reduce OPC complexity without reducing OPC effectiveness [34]; optimizing model-based OPC with respect to mask manufacturability and mask cost without sacrificing semiconductor device performance [35]; generating novel data flow preparations for the second write level of alternating aperture PSMs[3] [36]; designing chips with diagonal pathways for chip interconnect [6], [7]; and controlling the file size of pattern data by taking advantage of data hierarchy and data compaction [7], [37]. All these measures help contain or even reduce the number and complexity of sub-resolution features, with the effect of decreasing PG time and inspection time, the primary limiters of T_{max}. In particular, T_{max} should increase dramatically once designers are able to use "IP libraries" that contain standardized blocks of data whose PG times and inspection times are known to be short.

The impact of DFM is also likely to extend beyond a reduction of T_{max}. For example, a lower intrinsic PG time is likely to improve capital utilization because, at a constant rate of defect generation, a smaller fraction of masks is damaged by a defect. The mask yield improves, and the rework rate decreases accordingly. DFM practices also may allow a significant number masks to be written on the less expensive laser PG tools instead of the more expensive VSEB PG tools, a change that is likely to decrease their write time as well [7]. Finally, DFM has the potential of improving the timeliness of mask delivery to customers, preventing revenue loss that results from a delayed market entry [18].

The impact of mask costs on semiconductor manufacturing costs has historically been dwarfed by the cost of lithography tools and the cost of the fab as a whole. Therefore, mask costs have not been expected to dominate semiconductor manufacturing costs, even though they are growing at a much faster rate than the cost of lithography tools or the cost of a fab [8]. However, the impact of mask costs on semiconductor manufacturing costs may be asymmetric, with mask shops that produce a plethora of low

[3] Alternating Aperture PSMs constitute an advanced mask technology that is likely to comprise the leading edge of the 65-nm and 45-nm technology nodes due to superior resolution. [3], [42]

volume designs; e.g., foundries and makers of ASICs are more adversely affected than those who realize a few high volume designs, such as makers of DRAMS and microprocessors [2], [9], [38]. "For many foundry chips, where unit production is often well below 1000 wafers, mask costs are larger than wafer processing costs," and further increases in expenses pertaining to photomasks may begin to discourage these chip suppliers to adopt the 90 nm and smaller nodes [39]. An engineering manager at a mask shop agrees with this assessment:

> "If present trends continue, we shall observe a bifurcation of Moore's law. Chipmakers that produce a few bestsellers will continue on the Moore's Law trajectory. However, if you produce low volume designs, you are likely to stay at the 130-nm node for a long, long time."

Mask makers must either lower the price of leading-edge masks or cope with a reduction in demand for these products [38]. The latter option is particularly unpleasant, because capital equipment will remain idle unless the deteriorating demand for maturing 130 nm masks will be replenished by new demand from the 90 nm node; the marginal cost of production capacity will increase as a consequence. Long-term erosion in demand also limits a mask maker's ability to increase revenue by scaling up production.

To compensate for the asymmetric impact on semiconductor manufacturing, some mask makers and some foundries have instituted a service known as the shuttle, in which multiple designs (perhaps from multiple chipmakers) are placed onto one mask. The economics of this practice have been analyzed in [15], [16], and layout optimization schemes for multi-product masks have been proposed [11], [17]. Multi-product masks can reduce mask costs, but they also carry a significant risk of schedule slips and the related revenue loss [16]. One of the respondents in this study, the director of lithography at a semiconductor process development facility, explains how these might occur:

> "I am suspicious of using the shuttle service as a development vehicle when it is performed by a foundry. I do not know whether the knowledge gained in product development can be transferred to our environment, especially if we have to generate a new mask for volume production. Do we have to re-characterize the process? If so, having ten engineers work on this problem for a month is very costly.…Losing a month of market window when prices are dropping could be even worse."

All eight respondents in this study who were asked about multi-product masks indicated that they were difficult to optimize for each product. The lithography director from above explains:

> "If a mask set contains multiple designs, how to you optimize the process parameters for each design? The different designs could have different data densities and shapes; the optimal operating point for lithography and etch may be different for each design. Optimizing for the whole mask may create suboptimal conditions for each design."

Placing multiple layers of the same design has been proposed as an alternative to the shuttle. However, this practice reduces stepper throughput because only a part of a mask can be printed in one exposure. Partial exposure of the multi-layer mask also causes asymmetric thermal expansion of the mask, which generates mask alignment problems [15], [16].

VII. CONCLUSIONS

Our research has shown that a failure to contain the escalating costs of leading-edge photomasks will prevent photomask manufacturers from producing them profitably. Mask makers will have the option of ceasing to produce leading-edge photomasks or selling them below cost as part of a mask set, in the hope of recovering the losses from the other masks in the set. Selling leading edge-masks at a loss appears to be an unsustainable proposition for mask makers, given that the portion of class C masks within mask sets is increasing as integrated circuit feature sizes continue to shrink [3], [5]. A cessation of production would confront semiconductor manufacturers with some unpleasant choices. They can produce leading-edge masks internally and amortize their costs, a procedure that is being practiced by some foundries and makers of high volume integrated circuits. Alternatively, chipmakers can develop or enable the development of a (perhaps maskless) substitute technology at great expense [40]; or they can abandon Moore's Law [9].

Of all the previously discussed practices, design for manufacturability seems to hold the greatest promise for improving the profitability potential of photomask manufacturing and reducing the cost of photomasks. The various DFM efforts that are currently under way (e.g., [6], [7], [9], [34]-[37]) have the potential to significantly reduce the intrinsic PG time and inspection time, the primary drivers of marginal cost of production capacity. By contrast, attempts to increase the yield factors that contribute to the capital utilization rate in equation (3) will reach diminishing returns as the constituent factors of U(t) approach unity, and they may also be too expensive for smaller mask makers to afford. The limited size of the photomask industry is preventing a significant reduction in the cost of capital equipment, and the increasing complexity of leading-edge photomask manufacturing processes is likely to cause materials costs to move up rather than down.

Implementing DFM solutions to the mask cost problem will require key participants in the lithography value chain—circuit designers, chipmakers, toolmakers, mask makers, suppliers of photoresist—to collaborate in the development of an integrated lithography solution for future technology nodes, whose goal is to reduce W in equation (1), not just k_1 [3], [5], [8]. This means circuit designers must understand the capabilities and limitations of the technologies involved in the realization of their designs, and mask makers must understand how their products impact and are impacted by upcoming complementary technologies such as off-axis illumination and immersion lithography [3], [41]. The development schedule of all technologies must be coordinated to meet the demand schedule of semiconductor manufacturers, which varies substantially over time. Models that assess the financial performance of technology development and production in the lithography value chain must consequently take the time dependence of key cost and revenue indicators into account.

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LIST OF CAPTIONS FOR FIGURES AND TABLES

Table 1: Mask Classes

Table 2: Calculating the Marginal Cost of Production Capacity

Table 3: Profitability, Breakeven, and Scale

Table 4: Profitability, Breakeven, and Average Unit Sales Price

Table 5: Profitability, Breakeven, and Marginal Cost of Production Capacity

Table 6: Profitability, Breakeven, and Materials Cost

Figure 1: Evolution of key financial variables throughout the photomask manufacturing lifecycle (class C masks for the 130 nm node).

Figure 2: Varying Q(t), ceteris paribus.

Figure 3: Profitability as a Function of Scale (class C masks for the 130 nm node).

FIGURES AND TABLES

Table 1: Mask Classes

Mask Class	*OPC*	*PG Tool*	*PG Time (hours)*	*Inspect Time (hours)*	*Mask Unit Price (US$)*
A	no	Laser	<4	<4	$1k-$5k
B	yes	Laser	1 to 6	0.5 to 6	$5k-$40k
C	yes	VSEB	6 to 36	6 to 36	$20k-$120k

Table 2: Calculating the Marginal Cost of Production Capacity

	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
Mask Class	PG Time (hours/ mask)	T_{max} (Masks per Quarter per PG Tool)	U(t)	T(t) (Masks per Quarter per PG Tool)	c_{equ} (Nominal US$)	MC_{PC} (Nominal US$ per mask per quarter)
A	2	1080	0.66	720	$15 M	$21k
B	4	540	0.66	360	$20 M	$56k
C	6	360	0.66	240	$50 M	$208k

Table 3: Profitability, Breakeven, and Scale

Q_{pk} (Wfs./Qtr.)	NPV (t=10 yrs.) (Real US$)	Time to Breakeven (Years)
2000	$ 91.2 M	5.7
1500	$ 57.9 M	5.9
1000	$ 24.7 M	6.5
500	-$ 8.6 M	Never

Table 4: Profitability, Breakeven, and Average Unit Sales Price

Unit Price (t=0 yrs.) (Nom. US$)	Unit Price (t=4 yrs.) (Nom. US$)	NPV (t=10 yrs.) (Real US$)	Time to Breakeven (Years)
$120,000	$47,666	$ 72.6 M	5.3
$110,000	$43,694	$ 48.6 M	5.7
$100,000	$39,722	$ 24.7 M	6.5
$90,000	$35,750	$ 0.7 M	9.6
$80,000	$31,777	-$ 23.3 M	Never

Table 5: Profitability, Breakeven, and Marginal Cost of Production Capacity

MC_{pc} (Nom. US$/ Mask/Qtr.)	NPV (t=10 yrs.) (Real US$)	Time to Breakeven (Years)
$ 180 k	$ 42.3 M	5.6
$ 200 k	$ 29.9 M	6.2
$ 220 k	$ 17.4 M	6.9
$ 240 k	$ 4.9 M	8.4
$ 260 k	-$ 7.6 M	Never

Table 6: Profitability, Breakeven, and Materials Cost

Materials Cost (Nom. US$ per Mask)	NPV (t=10 yrs.) (Real US$)	Time to Breakeven (Years)
$4,000	$ 32.9 M	6.2
$5,000	$ 24.7 M	6.5
$6,000	$ 16.5 M	6.9
$7,000	$ 8.3 M	7.5
$8,000	$ 0.2 M	9.7
$9,000	-$ 8.0 M	Never

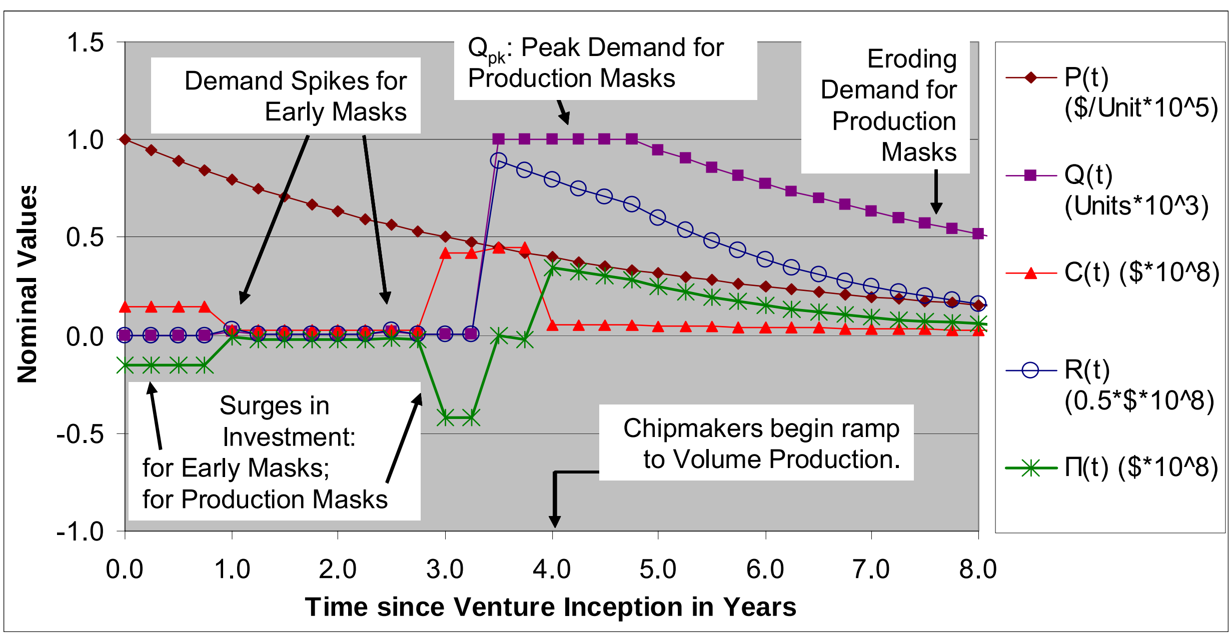

Figure 1: Evolution of key financial variables throughout the photomask manufacturing lifecycle (class C masks for the 130 nm node).

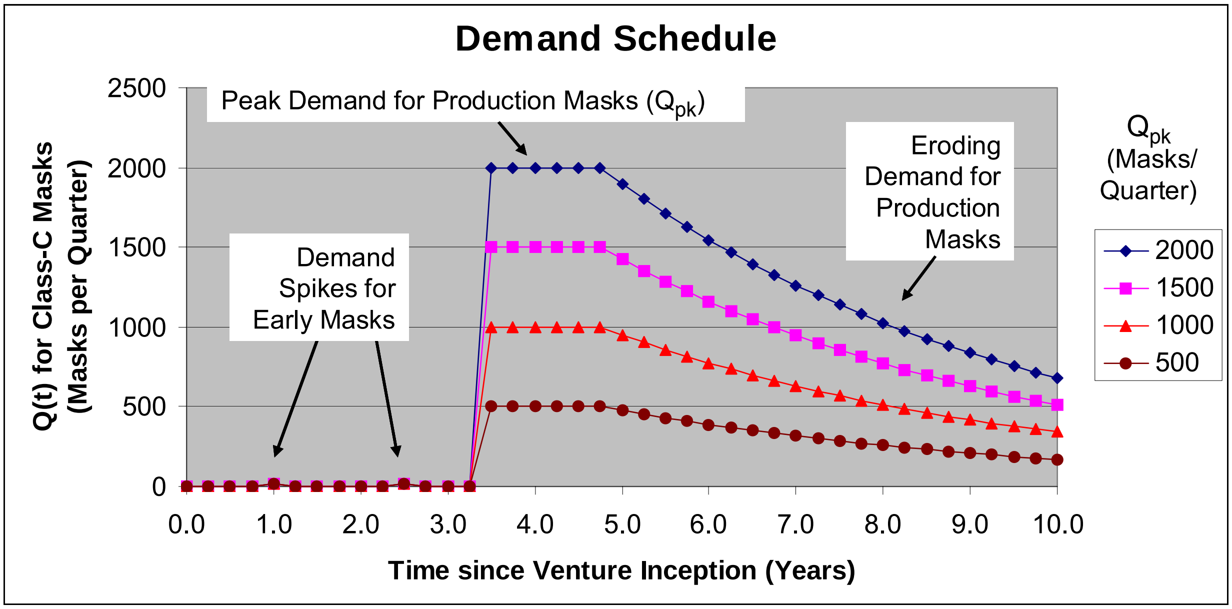

Figure 2: Varying Q(t), ceteris paribus.

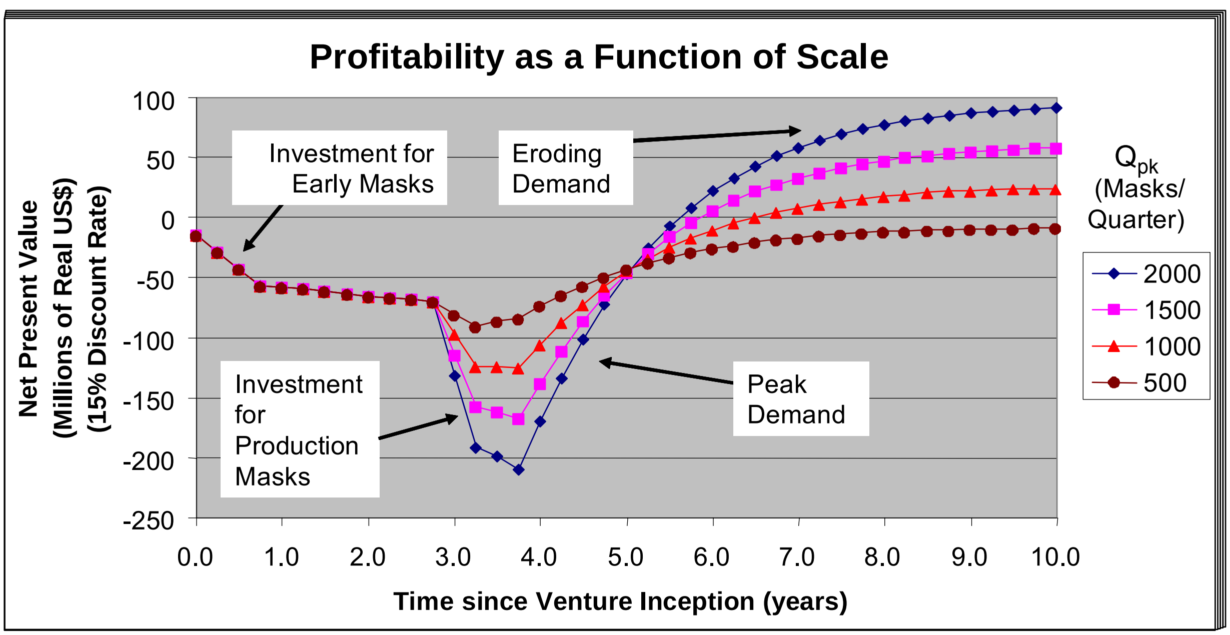

Figure 3: Profitability as a Function of Scale (class C masks of the 130 nm node).

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