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A CONTRACT OF PURCHASE COMMITMENTS ON SHARED YIELDS AS A RISK-SHARING MECHANISM AMONG FABLESS-FOUNDRY PARTNERSHIP

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ABSTRACT

This paper develops a simple cooperative-game model for an alliance with a design house and a foundry in a semiconductor supply chain. In particular, we attempt to investigate an emerging observed type of contracts among fabless-foundry partnership. It is termed the purchase commitments on shared yields contract. We emphasize the risk-sharing aspect on the contract by explicit modeling risk into the fabless and foundry's objective functions. It is shown that the optimal share of yields depends on two parties' expectations on prices of the products, risk-aversion, and scales of production. The optimal share is not directly related to the both firms' marginal cost of production. That is, this contract is a cost-invariant contract. A Nash bargaining solution for the wholesale price under this contract between fabless and foundry is also proposed.

1 INTRODUCTION

Semiconductor manufacturing cost continues to rise in the sub-wavelength process technology era (McGregor 2007). The average capital investment of a state-of-the-art 90nm and 65nm fab has now gone above US$5 billion. Fab costs in wafer size of 450mm is expected to be skyrocketing and may become formidable (LaPedus 2006, Hutcheson 2006, Chien et al. 2007). Process development cost also grows significantly with each generation of process technology. As a natural result, the manufacturing cost increases. For example, the cost of developing one mask set for circuit printing over silicon wafers in one fab have already costed US$1M at the 0.1μm technology node, which is expected to continue to increase exponentially. Such trends are shrinking the number of semiconductor companies with fabs and foundries to below 40 (McGregor 2007).

In the demand side of the semiconductor market, growths in consumer electronics and wireless/mobile communications have demanded for much higher variety, shorter life cycle time and lower costs for electronic products. Such uncertain and dynamic demands combined with the skyrocketing costs of fab and process development costs have made the risk of semiconductor manufacturing unprecedentedly high. Driven by the needs for risk mitigation and cost sharing, market changes have occurred among independent design and manufacturing companies (IDM), fabless and foundry semiconductor companies.

In the past few years, more and more IDM companies have adopted the fab-lite model by partnering with foundries and creating joint ventures (JVs). The fab-lite model is defined by the FSA as outsourcing 40 percent to 50 percent of manufacturing operations (Shelton 2003). Many companies such as Motorola, ADI, Sony, Renesas have taken the strategy. They have benefited in retaining some control of their own process technology, while gaining access to leading-edge foundry technology.

Alliance formation has also been a significant business model change for risk mitigation. Many semiconductor manufacturers and foundries have turned to joint process technology and/or fab capacity developments. For example, Chartered Semiconductor Manufacturing, IBM and Samsung have developed a new business model to provide a cohesive design and manufacturing ecosystem through their Common Platform™ technology (IBM 2006) for 300mm wafer fabs. Inotera Memories, Inc., a joint venture by Qimonda AG and Nanya Technology Corporation, is another example. The innovation in Inotera's business model combines the contribution of Qimonda's (a former memory division of Infineon) leading technology and Nanya's cost efficiency in mass production into competitiveness on the leading edge within the DRAM industry. Risks in process and capacity developments are shared by strategic alliance of joint venture and contractual collaboration in terms of purchase commitment on yields (Richter et al. 2005).

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In the supply chain management literature, there has been research on risk sharing via capacity commitments in a decentralized environment (for example, Özer and Wei (2006)). However, most of the existing models are only suitable for applications in analyzing interactions between fabless companies and pure-play foundries. Relatively few theoretic research investigates the contractual behavior of the alliance in semiconductor industry such as the emerging fab-lite model. Although there have been many descriptions about the emerging fab-lite model evolutions and the formation of alliances for risk mitigation of semiconductor manufacturing, there are few prescriptive models that may serve the needs for strategic analysis and design.

In this paper, we develop a cooperative-game theoretic model for contractual design of purchase commitments on yields as a risk-sharing mechanism among fabless-foundry partnership. The model in this paper explicitly takes market risks into considerations of the supply chain members to study an potentially emerging business model, a contract of purchase commitments on shared yields. Under this contract as in forming an alliance, the design house commits to purchase a certain share of the future yields that produced by the foundry fab. In addition to a traditional "money-for-chip" relationship, the design house contributes its proprietary semiconductor process technology and related know-how in the alliance to develop deeper and longer lasting relationship with the foundry. We model the market risks primarily as the price variations of the IC products supplied by the supply chain. We emphasize the risk-sharing mechanism of the contract for members of the supply chain facing a stochastic market environment. Our model shows that the optimal share of yields depends on the two firm's expectations on prices of the IC products, risk-aversion, and production scale. A Nash bargaining solution for the wholesale price of the IC products between fabless and foundry is also proposed. The model and results may also be applied as part of the contract analysis for fab-lite transitions of IDMs.

The remainder of the paper is organized as follows. Section 2 briefly reviews recent literature related to contracts in supply chain. In particular, we identify deficiencies of modeling supply chain contracting behavior if there is no risk consideration in a stochastic market environment. The setting of a simple supply chain model with explicitly risk considerations is addressed to discuss the contract of purchase commitments on shared yields as proposed. The optimal Risk-sharing rule and bargaining solution under the contract is analyzed in Section 4. Section 5 gives some concluding remarks.

2 CONTRACTS IN COORDINATING SUPPLY CHAINS

There is extensive literature studying the mechanism of contracts to coordinate the supply chain, i.e., to maximize the profit of the chain system, in stochastic environments. Most of the papers focus on how a specific type of contracts can achieve coordination in a decentralized supply chain through a set of measures (Lee and Whang 1999). These contracts, for example, include buy-back contracts (Pasternack 1985, Bernstein and Federgruen 2005), price-discount contracts , revenue-sharing contracts (Dana and Spier 2001, Cachon and Lariviere 2005), quantity-flexibility, and/or mixed of them (Cachon and Lariviere 2005). The design of these contracts centers on offering a scheme to align incentives of decentralized partners within the supply chain. These aligned incentives guide distributed decisions on polices of pricing, inventory, and capacity planning for counterparts of the supply chain.

A contract of coordinating distributed decision-makers in a non-cooperative game theoretic sense within a supply chain is theoretically attractive in the short run but is not necessary in a long-run allied partnership within the chain. In an alliance, the partners of the supply chain actually engage in repeated interactions rather in one-shot game. The incentive to deviate from the long-run cooperative outcome should be low among their partners. Some recent papers has raise this need based on the empirical observations and analyzed issues of supply chain coordination in repeated game settings (Terwiesch et al. 2005, Taylor and Plambeck 2007a, Taylor and Plambeck 2007b). However, this paper does not model the problem in a repeated game setting. Instead, we take the direct approach to analyze the possible long-run outcome in a cooperative game which may be a good candidate approach to study the behavior of alliances.

Additionally, existing literature in contracting supply chain usually assumes risk-neutral firms or implicitly models risk factors in the sense of 'mean' revenue or profit. It is suitable for markets of many products with a relative high profit margin and low price volatility. In high uncertainty and low profit margin supply chains, such as in the semiconductor industry, these assumptions might be no longer appropriate. This is pointed out by Van Mieghem (2003) that it seems natural to consider the variability in payoffs in addition to the mean payoff in decisions of capacity investments, the articles incorporating risk is surprisingly small.

When the firms in supply chains all care about risk, how the risk is transmitted through and what are the consequences of the transmission on the supply chain become crucial. For instance, a common practice in the semiconductor equipment supply chan is that the buyers initially place "soft" orders which only reveal their intent rather than "firm" orders which commit to purchase services/production provided by suppliers (Terwiesch et al. 2005). In advance of placing a firm orders by the buyers, the soft orders (often derived from buyer's forecasts on demand) serves as an informal information to guide the supplier's production capacity decisions (Cohen et al. 2003, Terwiesch et al. 2005; Taylor and Plambeck 2007a). Because these soft orders are subject to be revised and/or be cancelled by the buyers due to market uncertainty, this may lead to late availability of capacity provided by the supplier. That is, the supplier will hesitate to invest in capacity and fail to delivery products on right timing. This in turn creates an incentive for the buyers to inflate demand forecasts (soft orders) in order to assure sufficient supply need but these soft orders will eventually be revised downward and/or cancelled by the buyer. As a result, the classical prisoner's dilemma arises in noncooperative behavior among partners as observed empirically (Terwiesch et al. 2005).

Obviously, there are inevitable difficulties for firms in semiconductor industry to trap into the undesired dilemma. The buyers faces market demand uncertainty. Their soft orders vary from time to time in nature but partially resulted from lack of commitment to purchase as those orders initially placed. An empirical study reports that the cost of cancellation and holding hosts are about two times and three times higher than the delay cost for the semiconductor equipment suppliers (Cohen et al. 2003). It is not surprising to see the supplier's underinvestment in capacity in response to this variation in soft orders especially in an environment of risky demand and growing costs in acquiring production capacity.

In fact, the essentials of this problem are as follows. If the buyer places firm orders instead of soft orders like what others do in conventional newsvendor model with a pre-specified wholesale price, he has to bear the whole market risk alone. As the market risk overwhelmingly increases, the buyers would either withdraw from the market or have to shift (at least part of) the risk to others in order to survive in that market. Therefore, the buyer's attempt is understandable to shift market risk to their upstream suppliers through soft orders. The market forecasts carried by the soft orders are probably incorrect due to misaligned incentives. This will be, however, ultimately recognized by the supplier. If we taking the supply chain as a whole, the cause of the problem can attribute to "distributing the market risk in a wrong way."

As a consequence, the keys to solve the problem arising in a supply chain with highly volatile market and high costs of production capacity are how to appropriately allocate risk into chain partners and how to gauge the information sent by the buyers and received by the supplier. The risk cannot be assumed away as in other newsvendor models for regular supply chains. In contrast, risk should be explicitly taken into consideration of decision-making models for contracting semiconductor supply chains.

These, in line with the work by Wilson (1968) and Stiglitz (1974), motivate us to reconsider a long-run prospect over contracting semiconductor supply chains. A novel business model, a contract of purchase commitments on shared yields is proposed and analyzed in this paper. In stead of directly modeling repeated behaviors of supply chain's members (such as in Taylor and Plambeck 2007a, 2007b), we focus on a static cooperative outcome which might be considered as a long-run equilibrium ultimately reached through repeated interactions among partners of the supply chain.

The contract of purchase commitments on shared yields proposed in this paper has many appealing features in correspondence with the keys discussed earlier. First, the design house guarantees in prior to purchase a certain proportion of the yields produced by the foundry in the future may serve as a risk-sharing mechanism since the chain risk is diversified into partners. The double-marginalization problem in typical price-setting newsvendor model can also, at least partially be mitigated though this point is not directly addressed in our model. Second, the contract provides a novel type of orders between the soft order and the firm order. The control of how many to produce is now on the foundry's hand. The problem of soft order's variability and inflation can be alleviated. The foundry will not be too conservative to invest in capacity. Third, a contract of sharing production yields is similar to the contract of sharing revenue proposed by Cachon and Lariviere (2005). Under this contract, the foundry can partially benefit from the design house's marketing effort especially when market is in the upside. The allied partnership will be further established under this contract.

3 MODEL SETTINGS

Now consider an aggregated market demand of IC products, where different products are lumped into one aggregated type and will be referred to as “the product” in the remainder of the paper. Let the demand function for the product be p(q), where q is the demand quantity. In stead of modeling market uncertainty by allowing a stochastic demand, q, for the IC products (Cachon and Lariviere 2005), we attribute the market uncertainty to the variation of product price p. Let p be a random variable with a mean μ and variance σ_p^2.

Let there be a simple semiconductor supply chain with two risk-averse firms, a design house and a foundry fab. The foundry owns wafer fabrication facilities and manufacturing and process knowledge. The design house or IDM designs IC products and owns some know-how of semiconductor processes and intellectual properties (IPs). We study a particular contract recently observed in the semiconductor industry. It is called *a purchase commitment contract* in which the design house commits to purchase a certain share (denoted by α, $\alpha \in [0,1]$) of future yields of the foundry. The foundry therefore keeps 1-α of the yields. In addition, the design house contributes its proprietary semiconductor design and/or process technology in exchange of the foundry's manufacturing service and pays the foundry a wholesale price w_T per unit of the IC product. The design house's input level of proprietary design and/or process technology is denoted by M. The capacity supplied by the foundry fab is denoted by K. Let Y=Y(K,M) be the effective yield function which is increasing in K and M but at a decreasing rate. To be specific, Y_i and Y_{ij} denotes the first and second partial derivatives of Y with respect to i and j, for i and j =K, M. Let C_K and C_M represent the unit cost of K and M, respectively. A well-behaved concave function for yield maximization requires that $Y_K > 0$, $Y_M > 0$, $Y_{KK} < 0$, and $Y_{MM} < 0$.

To explicitly address the impact of risk on this supply chain partnership, we consider a specific utility function $U = U(\Pi, \sigma_\Pi)$ for a risk-averse firm in this study where Π is the profit random variable and σ_Π = sqrt(Var(Π)) is the associated standard deviation of profits. This form of utility function assumes the firm's utility is positively correlated to profit but decreasing in the variation of profit. That is, a *risk-averse* firm prefers less uncertainty given a profit level. Formally, the expected utility maximization problem can be approximated by

$$\max \; EU = E(\Pi) - \frac{1}{2} r\sigma_\Pi^2$$

where r>0, a positive constant representing the degree of risk aversion for the firm (Van Mieghem 2003, Myerson 2005). Namely, a higher r value indicates the firm is more risk-averse. In this functional form, given the profit level, the utility of a firm is adjusted downward for variance of the profit with the firm's subjective degree of risk-aversion. This risk-adjusted utility level is called certainty equivalent (CE) utility level which is the amount of profit such that the decision marker would be indifferent between the risky outcome and this amount of profit for sure. For any pair of (Π, σ_Π), one can find another (Π', 0) pair to achieve the same expected utility level but without uncertainty. Our model focuses on the price variation as the source of market uncertainty but allows each firm may have different expected prices and degrees of risk-aversion from each other.

In specific, the design house's profit is $\Pi_D = \alpha(p - w_T)Y - C_M M$. The expected profit is $E\Pi_D = \alpha(\mu - w_T)Y - C_M M$ and variance of the profit is $\sigma_D^2 = \alpha^2 Y^2 \sigma_p^2$. Let r_D and r_F denote degrees of risk-aversion for the design house and the foundry, respectively. Therefore, the design house's problem for maximizing expected utilities becomes to maximize

$$EU_D = \alpha(\mu_D - w_T)Y - \frac{1}{2} r_D \alpha^2 Y^2 \sigma_p^2 - C_M M \qquad (1)$$

In similar, the foundry fab's expected profit is $E\Pi_D = (1-\alpha)\mu Y + \alpha w_T Y - C_M M$ and variance of the profit is $\sigma_F^2 = (1-\alpha)^2 Y^2 \sigma_p^2$. The foundry fab's problem is to maximize

$$\begin{aligned} EU_F &= (1-\alpha)(\mu_F + w_T)Y \\ &\quad - \frac{1}{2} r_F (1-\alpha)^2 Y^2 \sigma_p^2 - C_K K \end{aligned} . \qquad (2)$$

It is necessary to assume EU_D and EU_F are nonnegative to ensure that the firms are interesting in this market.

4 ANALYSIS IN THE SUPPLY CHAIN WITH RISK-SHARING

4.1 Optimal Risk-sharing within the Supply Chain

Taking the supply chain as an alliance, the allied chain maximizes the joint expected utility of the two firms, i.e.,

$$\begin{aligned} \text{Max} \quad & \alpha(\mu_D - w_T)Y - \frac{1}{2} r_D \alpha^2 Y^2 \sigma_p^2 - C_M M \\ & + (1-\alpha)(\mu_F + w_T)Y - \frac{1}{2} r_F (1-\alpha)^2 Y^2 \sigma_p^2 - C_K K \cdot \end{aligned}$$

The first order conditions are

$$Y_M \left[\alpha H_D + (1-\alpha) H_F\right] = C_M, \qquad (3)$$

$$Y_K \left[\alpha H_D + (1-\alpha) H_F\right] = C_K, \qquad (4)$$

$$YH_D - YH_F = 0, \qquad (5)$$

where $H_D = \mu_D - r_D \alpha Y \sigma_p^2$ and $H_F = \mu_F - r_F (1-\alpha) Y \sigma_p^2$. H_D and H_F can be thought risk-adjusted expected prices of the IC product to the design house and foundry, respectively. The last first order condition suggests

$$H_D = H_F \cdot \qquad (6)$$

This indicates the chain can achieve utility maximization by equating two firms' risk-adjusted prices. Substitute $H_D = H_F$ into (3) and (4) and simplify to obtain

$$Y_M H_D = C_M, \qquad (7)$$

$$Y_K H_D = C_K \cdot \qquad (8)$$

These two conditions jointly determine the optimal inputs M, K, and total yields Y. Furthermore, $H_D = H_F$ plays an important role to allocate the optimal shares of the yields to the firms. The optimal share (α^*) for the design house is

$$\alpha^* = \frac{\mu_D - \mu_F + r_F Y \sigma_p^2}{(r_D + r_F) Y \sigma_p^2} \cdot \qquad (9)$$

The derivation of the rule is straightforward by using the fact that $H_D = \mu_D - r_D \alpha Y \sigma_p^2$, $H_F = \mu_F - r_F(1-\alpha)Y\sigma_p^2$, and $H_D = H_F$.

Observe that α* does not seem directly related to input efforts and marginal costs. However, this mean that this contract of purchase commitments on shared yields proposed here is a cost invariant contract and is suitable for various situations of costs. It depends on the two firms' expectations on prices of the products, degrees of risk-aversion, and scales of yields (i.e., Y).

There are many insights based on the implications from (9). First, let us consider a conventional wholesale-price business model in which the design house hold the total yields Y (i.e., α=1) and pays w_T per unit to the foundry. in the conventional wholesale-price model business model, the design house holds all yields, $\hat{Y}$, of the IC product. The price risk all falls on the design house while the foundry bears no risk of possible market price variation because he receives w_T per unit of yield for sure. This would discourage the design house from entering a market with expected high risk.

Furthermore, note that α=1 requires $\mu_D = \mu_F + r_D Y \sigma_p^2$ according to (9). It indicates that the conventional wholesale-price business model will only succeed when the design house's expectation on the price of the IC products is high enough to the level $\mu_F + r_D Y \sigma_p^2$. Namely, if the design house has to take all market risk alone, the wholesale-price business model will easily fail when the market is volatile in terms of price variation (i.e., σ_p^2 increases). Facing a higher market risk alone, the design house will have no interests in such a market and therefore order nothing from the foundry.

An special case is worthy of notice. If both parties have the same consensus the expectations on price (i.e., $\mu_D = \mu_F$), the optimal share held by the design house by (9) reduces to a simple form

$$\alpha^* = \frac{r_F}{r_D + r_F}.$$

Under this situation, α* only depends on two parties' degree of risk-aversion and is independent of total yields Y and price risk. That is, the design house take α* of the total yields will be always optimal whatever the price risk is. It also suggest that this type of contracts studied in this paper has nice properties to adapt to variation in costs.

Finally, consider a fully integrated supply chain. The centralized supply chain's problem is to maximize

$$EU_D = (\mu_D - w_T)Y - \frac{1}{2} r_D Y^2 \sigma_p^2 - C_M M + w_T Y - C_K K. \tag{10}$$

The first order conditions require

$$Y_M \hat{H}_D = C_M. \tag{11}$$

$$Y_K \hat{H}_D = C_K. \tag{12}$$

where $\hat{Y}$ denotes the optimal quantity of yields and $\hat{H}_D = \mu_D - r_D \hat{Y} \sigma_p^2$ under this situation.

In this integrated supply chain, $\hat{H}_D$ is lower than H_D determined in (7) and (8) since $\mu_D - r_D \hat{Y}\sigma_p^2 < \mu_D - r_D \alpha \hat{Y} \sigma_p^2$ for α<1. This suggests the quantities $\hat{Y}$ produced in the integrated supply chain will be less than in a allied supply chain with a purchase-commitment contract. Besides, with a smaller production capacity, it might lead to a higher marginal cost of production of the foundry.

4.2 Bargaining within the Supply Chain with Risk-Sharing

It is demonstrated that the contact of purchase commitments on yields proposed in the previous section can coordinate a semiconductor supply chain especially when the market volatility is increasing. However, a rule for allocating the chain's profit between the design house and foundry is needed in practice given the optimal allocation of the total yields. In bargaining literature, the Nash fixed threat bargaining model is often proposed (Chatterjee et al. 2002, Taylor and Plambeck 2007b). The Nash solution for the unit wholesale price w_N is to choose an w_T by maximizing the product of the two parties' profits given α*

$$\text{Max} \left(\alpha \mu_D Y - \frac{1}{2} r_D \alpha^2 Y^2 \sigma_p^2 - C_M M - w_N Y\right) \times \left((1-\alpha)\mu_F Y - \frac{1}{2} r_F (1-\alpha)^2 Y^2 \sigma_p^2 - C_K K + w_N Y\right). \tag{13}$$

The first order condition is

$$[\alpha \mu_D Y - \frac{1}{2} r_D \alpha^2 Y^2 \sigma_p^2 - C_M M - (1-\alpha)\mu_F Y + \frac{1}{2} r_F (1-\alpha)^2 Y^2 \sigma_p^2 + C_K K - 2 w_N Y] Y = 0. \tag{14}$$

We may solve optimal w_N from (14) to obtain

$$w_N = \frac{1}{2}\left(\frac{EU_D - EU_F}{Y}\right). \tag{15}$$

Note that, we may let $w_N = \alpha w_T$, therefore $w_T = (1/\alpha)\, w_N$. In fact, this formulation states that the two parties just equally share the chain's profit. This is because it is not difficult by rearranging (14) to show

$$EU_D - w_N Y = EU_F + w_N Y = \frac{1}{2}\left(EU_D + EU_F\right). \tag{16}$$

The above analysis assumes the two parties have the same bargaining power within the supply chain. If one of the two parties is in competitive market, the other party may have a stronger bargaining position to gain more than $0.5(EU_D+EU_F)$.

5 CONCLUDING REMARKS

As the capital investment and process costs continue to rise, and the demand become more volatile in the semiconductor industry, there are many IDMs engaging in partnering with pure-play foundries and creating join ventures toward a closer allied relationship or the fab-lite business model over the past years. However, most of the literature studying the interactions between members of supply chains stem from the non-cooperative game approach. It is contributive in analyzing coordination issues for decentralized supply chains but may not be suitable for the supply chain as a strategic alliance.

In this paper, a simple cooperative-game model with explicitly considerations of price riskinto firms' objective function in a semiconductor supply chain is developed to investigate the contractual design for the design house and the foundry. A contract of purchase commitments on shared yields is proposed and analyzed. We identify that the optimal share of yields depends on the two firm's expectations on prices of the IC products, risk-aversion, and production scale. It is shown that this type of contracts can serve as a risk-sharing mechanism to achieve coordination in the supply chain. Furthermore, under this contract, the problem of information distortion carried by orders from the design house to the foundry can be alleviated and the foundry will not be too conservative to invest in capacity. A bargaining solution in determining the wholesale price between the design house and the foundry is also demonstrated.

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