ANALYSIS OF FLEXIBLE DESIGN OPTIONS FOR MIXED-SIGNAL INTEGRATED CIRCUIT PRODUCTS

 MASSACHUSETTS INSTITUTE OF TECHNOLOGY

 IDS.332 FINAL REPORT

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 12/12/2017
Agenda

▶ Background
▶ Problem Statement
▶ Analysis Approach
▶ Recommended Strategy
▶ Questions
Background: Semiconductor Industry

- $378 Billion Industry

- Expected to grow 12% in 2017

- Historically, driven by Economy of Scale (EoS) benefits associated with Moore’s law

- Recent years have focused on energy-efficiency rather than speed

- Due to the capital investment required, companies are re-thinking their plans in fine-line geometries

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Additional Information
World: World Semiconductor Trade Statistics; 2017

Sources
WSTS; SIA
### Background: IC Integration Levels

<table>
<thead>
<tr>
<th>Integration Type</th>
<th>IC Process</th>
<th>IC Die</th>
<th>Package(s)</th>
<th>Resistors, Inductors, Capacitors (RLC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System in Package (SiP)</strong></td>
<td>1 or more</td>
<td>2 or more</td>
<td>1</td>
<td>Few (optional)</td>
</tr>
<tr>
<td><strong>Heterogeneous (Hetero)</strong></td>
<td>2 or more</td>
<td>1 or more</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td><strong>Monolithic (Mono)</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>None</td>
</tr>
</tbody>
</table>
Introduction:
Economy of Scale (EoS) Benefits in Monolithic Integration

EoS compels companies to:

▶ **Build Big**
  - To overcome initial Non-Recurring Engineering (NRE) costs
  - Compels companies to integrate super-set of all target customer’s functionality demands

▶ **Commit Early**
  - To reduce mask sets
  - Customer configurations must be known in advance and included in the initial design

▶ **Couple Developments**
  - All functionality must be finished prior to mask set creation
  - Exposes companies to competitive threats since customers cannot see actual working silicon until all developments complete
Introduction:
Monolithic Integration Challenges

Building Big, Committing Early, and Coupling Developments:
▶ Creates all-or-nothing dependencies
▶ Increases the project risk under uncertainty
▶ Hinders the project from quickly responding to future customer future needs
▶ Increases dependent complexity
Problem Statement

To maximize the Net Present Value (NPV) of a mixed-signal Integrated Circuit (IC) product

By creating a flexible development strategy in the face of uncertainty*

Using decision rules to modify System in Package contents as demand changes

*uncertain product demand,
*uncertain project costs, and
*uncertain project execution timelines
Target Applications

1) Transmit (Tx) Only Products

2) Receive (Rx) Only Products

3) Transceiver (Tx and Rx) Products
Analysis Steps

**Step 1**
Develop NPV valuation model of Mono & SiP Integration for IC Products

**Step 2**
Calculate Deterministic NPV for Mono Integration using Static Inputs

**Step 3**
Perform Sensitivity Analysis on NPV Model (Tornado Diagram)

**Step 4**
Perform Probabilistic NPV Analysis on Mono Integration using Monte Carlo (n=2000)

**Step 5**
Perform Probabilistic NPV Analysis on Mono & SiP Integration using Monte Carlo (n=2000)
Base Case + Flexible Option #1
Monolithic Integration (One Mask – One Die)

- **Mask Set**
  - Transceiver Wafer
  - Transceiver Die
  - Powered Down Region

- **Products**
  - **Tx Only Products (Rx Powered Down)**
  - **Tx and Rx Combo Products**
  - **Rx Only Products (Tx Powered Down)**

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Flexible Option #2
System in Package Integration (One Mask – Two Die)

½ Tx + ½ Rx Wafer

- Tx Only Products
- Tx and Rx Combo Products
- Rx Only Products

= Tx Die
= Rx Die

Mask Set
Flexible Option #3
System in Package Integration (Two Mask - Two Die)

Tx Mask Set

Tx Wafer

Tx Only Products

Rx Mask Set

Rx Wafer

Tx and Rx Combo Products

Rx Only Products

= Tx Die

= Rx Die

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## Comparison Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Case</th>
<th>Flexible Option #1</th>
<th>Flexible Option #2</th>
<th>Flexible Option #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integration Type</td>
<td>Mono</td>
<td>Mono</td>
<td>SiP</td>
<td>SiP</td>
</tr>
<tr>
<td># Mask Sets</td>
<td>One</td>
<td>One</td>
<td>One</td>
<td>Two</td>
</tr>
<tr>
<td># Die</td>
<td>One</td>
<td>One</td>
<td>Two(Tx,Rx)</td>
<td>Two(Tx,Rx)</td>
</tr>
<tr>
<td>Capacity Assumptions</td>
<td>Static</td>
<td>Dynamic</td>
<td>Dynamic</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Capacity Dependency (Tx)</td>
<td>None</td>
<td>None</td>
<td>Tx=Rx</td>
<td>None</td>
</tr>
<tr>
<td>Schedule Dependency (Tx)</td>
<td>max(Tx,Rx)</td>
<td>max(Tx,Rx)</td>
<td>max(Tx,Rx)</td>
<td>Tx</td>
</tr>
<tr>
<td>Schedule Dependency (Rx)</td>
<td>max(Tx,Rx)</td>
<td>max(Tx,Rx)</td>
<td>max(Tx,Rx)</td>
<td>Rx</td>
</tr>
<tr>
<td>Cost Dependency (Tx)</td>
<td>Tx + Rx</td>
<td>Tx + Rx</td>
<td>Tx</td>
<td>Tx</td>
</tr>
<tr>
<td>Cost Dependency (Rx)</td>
<td>Tx + Rx</td>
<td>Tx + Rx</td>
<td>Rx</td>
<td>Rx</td>
</tr>
</tbody>
</table>
Flexible Option #2 (SiP Integration w/ one mask, two die)
- provided the highest average NPV value at $13.2M.
- Improves the average NPV by $2.4M to $9M relative to the other options.
- 90% probability that the NPV will lie between:
  - P5 = +$0.5 and
  - 95 = +$25.9 million,
## Results Summary

<table>
<thead>
<tr>
<th>Evaluation Metrics</th>
<th>Base Case</th>
<th>Flexible Option #1</th>
<th>Flexible Option #2</th>
<th>Flexible Option #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV (VaR₅) - 90% confidence min</td>
<td>-$8.9M</td>
<td>-$6.3M</td>
<td>-$3.1M</td>
<td>-$5.4M</td>
</tr>
<tr>
<td>NPV (VaR₁₀) - 80% confidence min</td>
<td>-$6.0M</td>
<td>-$2.9M</td>
<td>$0.5M</td>
<td>-$1.8M</td>
</tr>
<tr>
<td>NPV (mean)</td>
<td>$4.0M</td>
<td>$9.4M</td>
<td>$13.2M</td>
<td>$10.8M</td>
</tr>
<tr>
<td>NPV (VaG₉₀) - 80% confidence max</td>
<td>$14.1M</td>
<td>$21.2M</td>
<td>$25.9M</td>
<td>$23.4M</td>
</tr>
<tr>
<td>NPV (VaG₉₅) - 90% confidence max</td>
<td>$17.0M</td>
<td>$24.6M</td>
<td>$29.5M</td>
<td>$27.0M</td>
</tr>
<tr>
<td>NPV (std dev)</td>
<td>$7.9M</td>
<td>$9.6M</td>
<td>$10.1M</td>
<td>$10.0M</td>
</tr>
<tr>
<td>Flexibility Value (mean)</td>
<td>-</td>
<td>$5.5M</td>
<td>$10.3M</td>
<td>$7.5M</td>
</tr>
<tr>
<td>Fixed Cost (mean)</td>
<td>$18.1M</td>
<td>$18.2M</td>
<td>$18.1M</td>
<td>$22.3M</td>
</tr>
<tr>
<td>Fixed Cost (std dev)</td>
<td>$1.4M</td>
<td>$1.4M</td>
<td>$1.4M</td>
<td>$1.4M</td>
</tr>
</tbody>
</table>

*Bold entries represent the best alternative between options
Recommended Decision Making Strategy: SiP Integration w/ one or two mask, two die

- **Tx Dev. Team**
- **Rx Dev. Team**
- **System Architects**

Legend:
- Mask Set Plans
- Trash
- Market Information
- Key Decision Point
- IC Manufacturing Process
- Money
- Transceiver Products
- Rx Only Products
- Tx Only Products

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Recommended Strategy

▶ Hybrid approach between Flexible Option #2 and Flexible Option #3
▶ Plan for two separate Tx and Rx die
▶ Defer decision on # of mask sets needed (one vs two), until Rx or Tx developments are close to completion
▶ If one development team finishes early, management can decide to either
  ▪ Pay for two mask sets or
  ▪ Wait for second development to finish and only pay for one mask set
  ▪ Decision made at time when additional information would be known about the market demand.
▶ Minimizes the silicon cost for Tx and Rx Only applications – enables Tx/Rx Integration!

See previous slide for visual
Benefits of Recommended Flexible Strategy

- **Increases Project Flexibility due to Deferred Commitments**
  - Pushes integration decisions to later point in time – when more information available
  - Since customer demand dynamically changes over time:
    - Flexible Approach Enables Future Expansion – Allows new combinations of integrated products through laminate changes (simpler and cheaper to modify than silicon mask layers)
    - Allows Performance Scaling – With separate semiconductor die, opportunity to optimize functionality for RF, Analog or Digital content

- **Reduces Costs (Tx Only & Rx Only)**
  - Tx and Rx functionality exist on separate die which minimizes the full-factory cost of the silicon for Tx and Rx Only applications and improves the Gross Margin (GM) on those products.

- **Decouples Developments**
  - Each subsystem can be given its own die or even mask set
  - Subsystems developed independently
  - Reduces product development risk for Tx Only and Rx Only products (removes the all-or-nothing barrier)
SiP Integration strategy

- Provided the highest NPV ($13.2M)
- Scored the best overall according to the evaluation metrics (22% increase)
- Minimizes downside risk and maximizes upside opportunities

Flexible SiP options:

- Defer integration decisions, which...
- Enables future expansion by...
- Allowing new product configurations as market demand changes
  Resulting in...

Increased Value
References

▶ [8] https://ycharts.com/companies/ADI/gross_profit_margin
▶ [11] Images:
  - Clipart Icons made by Freepik from www.flaticon.com
## Implementation Barriers

<table>
<thead>
<tr>
<th>Type</th>
<th>Barrier</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>Requires development of <strong>slow chip-to-chip</strong> data and control <strong>interfaces</strong> between Tx and Rx die.</td>
<td><strong>Planning ahead</strong> to ensure buy-in by soliciting feedback from all relevant stakeholders, and creating a formal specification for these interfaces with the goal of handling at least 2 generations of products.</td>
</tr>
<tr>
<td>Management</td>
<td><strong>Future managers do not know about capability</strong> to create new products from Tx or Rx die.</td>
<td><strong>Create an integrated product delivery team</strong> which would collaborate between design and decision making teams.</td>
</tr>
<tr>
<td>Management</td>
<td><strong>Key managerial stakeholders could block the development</strong> of Tx or Rx standalone die – or any developments which would prevent Monolithic transceiver development.</td>
<td><strong>Develop a long-term roadmap</strong> outlining future transceiver products from the Tx and Rx die. This roadmap must include a game plan which is understood by the key managerial stakeholders.</td>
</tr>
<tr>
<td>Competitive</td>
<td><strong>External competitive pressure</strong> forces the company to use Monolithic Integration to take advantage of the Economy of Scale benefits.</td>
<td><strong>Combine the Tx and Rx die into a single Monolithic die.</strong> At the same time, continue to support the Tx and Rx die in the Feasibility** of the SiP solution.</td>
</tr>
<tr>
<td>Feasibility</td>
<td>Overhead associated with two die solution may require <strong>replicated logic</strong> (bias, calibrations, etc.) which would <strong>affect the feasibility</strong> of the SiP solution</td>
<td>During this investigation, the recommendations listed above hold, so long as the replicated logic does not represent &gt;25% overhead on the two die SiP solution. <strong>Ensure replicated logic does not represent &gt;25% overhead.</strong></td>
</tr>
</tbody>
</table>
Background:
IC Manufacturing Process

1) Circuit Designers

2) Mask Set Instructions (gdsii)

3) Semiconductor Fabrication Plant (FAB)

4) Silicon Wafers

5) Wafer Processing + 6) Packaging Process

7) Packaged IC Products

Raw Materials (Gold, Copper, Silicon)

Verification/Testing
Wafer Processing (Generic)

Mask Set → Wafer → Wafer Dicing → Bare Die

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Wafer Processing (½ Tx + ½ Rx Wafer)

Mask Set

Wafer

1/2 Tx + 1/2 Rx Wafer

Wafer Dicing

Tx Die

Rx Die
## Model Uncertainty Assumptions

<table>
<thead>
<tr>
<th>ID</th>
<th>Uncertainty</th>
<th>%</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Realized demand in qtr 1 within</td>
<td>50%</td>
<td>+/- from projection</td>
</tr>
<tr>
<td>2</td>
<td>Additional demand by qtr 10</td>
<td>50%</td>
<td>+/- from projection</td>
</tr>
<tr>
<td>3</td>
<td>Additional demand after qtr 10</td>
<td>50%</td>
<td>+/- from projection</td>
</tr>
<tr>
<td>4</td>
<td>Annual volatility of demand growth</td>
<td>50%</td>
<td>of growth projection</td>
</tr>
<tr>
<td>5a</td>
<td>Development Schedule Increase (mean)</td>
<td>18%</td>
<td>normal dist. from projection</td>
</tr>
<tr>
<td>5b</td>
<td>Development Schedule Increase (std dev)</td>
<td>21%</td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td>Development Cost Increase (mean)</td>
<td>39%</td>
<td>normal dist. from projection</td>
</tr>
<tr>
<td>6b</td>
<td>Development Cost Increase (std dev)</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>7a</td>
<td>Gross Margin (mean)</td>
<td>0%</td>
<td>normal dist. from projection</td>
</tr>
<tr>
<td>7b</td>
<td>Gross Margin (std dev)</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Wafer Cost</td>
<td>10%</td>
<td>+/- from projection</td>
</tr>
<tr>
<td>9</td>
<td>Yield Variability</td>
<td>2.5%</td>
<td>+/- from projection</td>
</tr>
</tbody>
</table>
Model Sensitivity

Monolithic Integration
Deterministic NPV = $9M

SiP Integration
Deterministic NPV = $14M
Flexible Option #1 Decision Making Process (Mono Integration)

**Tx Dev. Team**

- System Architects
- Rx Dev. Team

1. **Market Information**
2. **IC Manufacturing Process**
3. **Money**
4. **Trash**

**Key Decision Point:**

- **Tx Only Products**
- **Transceiver Products**
- **Rx Only Products**

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Flexible Option #2 Decision Making Process (SiP Integration)

1. Decision point: Define Product Type
   - Tx Only Products
   - Transceiver Products
   - Rx Only Products

2. Decision point: Integrate ICs
   - Tx ICs
   - Rx ICs
   - Tx/Rx ICs

3. Decision point: GI and System Integration
   - Mask Set Plans
   - Market Information
   - Key Decision Point

4. Decision point: Manufacturing Process
   - Trash
   - Money

- Tx Dev. Team
- Rx Dev. Team
- System Architects
Flexible Option #3 Decision Making Process (SiP Integration)

1. Rx Only Products
2. Transceiver Products
3. Rx Only Products
4. Tx Only Products

Tx Dev. Team

System Architects

Rx Dev. Team

Key Decision Point

Mask Set Plans

Market Information

Trash

Manufacturing Process

Money