Chapter 19
Transferring Technology for Production

During the foundry evaluation and selection process, the foundry received only enough information about your company’s technology to assess the business opportunity and to provide a quote for the initial feasibility batch. They did not receive enough information for actually making your product. After the contract has been signed between your company and the foundry, and a purchase order issued, the transfer of your company’s detailed design and fabrication information to the foundry team must begin, a period known as “tech transfer.” This is the period in which your company will teach the foundry what you have made and learned so far, so that they can begin to set up their equipment and processes in order to replicate your product in higher volumes.

Preparing for Tech Transfer

When it is time to begin tech transfer to the foundry, you will first need to provide the foundry team with very detailed information on your technology. Review Chap. 16 for a list of all of the documentation you should already have on your product technology; if you did not have it previously ready, now is the time to do it.

Determining What Information to Share

When preparing information for transfer to volume manufacturing, it is helpful to have a strategy and to be organized. If you were to just dump a bunch of data on the foundry, they might eventually work their way through it, but you would pay for their effort in both time and money. Focus first on the process flow of record and mask layout (see next section) that you would like to transfer to the foundry and build up the supporting documentation from there, sharing more details on process steps that affect critical features of your device. Also, listen to the questions the
foundry team asks regarding the process flow. Those questions likely reflect where they might be less experienced or where they have learned that those details are the difference between success and failure.

There are also trade-offs between compartmentalizing information to protect IP versus sharing information to engage partners in efficient problem solving. Ideally, concerns regarding data protection, potential conflicts of interest (such as the foundry also making your competitor’s product, a common situation), and business strategy (pure play vs. mixed use foundries) were addressed during the foundry selection process. In general, we recommend that you not be too paranoid. If you know a special trick for getting just the right flavor of oxynitride from a PECVD tool that will improve your device’s yield or performance, share it with the foundry team. Foundries know lots of processes and see many MEMS designs. When it comes to wafer fabrication processes, they probably already know the recipes you might think of as “secrets” and withholding information essential to your device’s success will just slow down progress.

If you are trying to compartmentalize information to protect very sensitive product IP, avoid sharing the back-end process information, test data and analysis, and so on, with the foundry and disclose only those details relevant to the foundry’s work. For example, if a special anti-stiction coating helps your device to perform better, and your company will apply it to finished wafers, not the foundry, then do not put details about that coating in your process documentation. Instead, disclose only your requirements, for example, the wafer must not have material X because it is incompatible with your coating process. Creating and enforcing some simple boundaries can effectively protect sensitive or trade secret information without jeopardizing your overall fabrication process.

**Process of Record (POR)**

The POR provided to the foundry needs to be much more detailed than what was provided during the foundry quote and selection process. The POR is not just a document, it is also a training tool for foundry engineers who are about to work on your product. Write it as if you were training someone new to run your process. (See Chap. 16 for more details.)

At a bare minimum, the POR that is transmitted to the foundry should include:

- An (x, y) mask layout with defined layers.
- A written process flow.
- List of critical process tolerances.
- A 2D cross-section (drawn to scale) for each process step.

Additional process information that can be helpful include:

- Examples of previous process designs and iterations, providing an overview of the history of how the design evolved to where it is today.
- What processes you had previously tried and what worked and did not work.
• 3D renderings of the process steps
• Sample die to the foundry engineers.
• SEM or microscope images of each process step from prior runs.

The foundry MEMS engineers will know how to interpret the information on your runsheet in order to set up their own process runsheet for their specific set of tools. Transferring the additional knowledge items listed above could save the foundry team from revisiting processes or design changes that you have already tried and discarded. Your engineering team should also be able to explain to the foundry’s engineers why you have made certain process choices and to provide insight on which processes might be adjusted without harming device function versus which ones must remain as they are.

Planning

Before starting the tech transfer, it is a good time to revisit your company’s go-to-market plans and product roadmap. The project timeline you set with the foundry must be informed by your company’s needs and goals, as well as by any downstream back-end processes, assembly and tests that are needed to finish product fabrication and to prepare products for sampling or sale to customers. Telling the foundry you need wafers as soon as possible is not very informative; everyone says that. Instead, explaining why certain wafers are needed by certain dates and how those milestones link to your company’s product ramp-up, and eventually, volume wafer orders, will get their attention and recruit their efforts to keep your wafers’ process schedule on track.

Similarly, communicate within your company about realistic tech transfer timelines, which have been confirmed by the foundry, so that your executives and investors know what to expect. As you can see from Fig. 19.1, you are about to begin a foundry production development effort that will span at least 1–1.5 years.

Initial Transfer

In the semiconductor industry, which has the benefit of being several decades more mature than the MEMS industry, tech transfer occurs via software automation: automated design rule checking of photomask data, process rule checks, and data upload to the foundry. In the MEMS industry, in all but a few cases\(^1\), tech transfer still happens the old-fashioned way: teams of engineers exchanging documents and talking

\(^1\)These few cases usually involve established foundry platform processes, as mentioned in Chap. 11. If you are transferring a design and process to a very high-volume foundry such as TSMC or a large captive foundry, the technology transfer process may be formalized and you would need to follow their instructions. High-volume or captive MEMS foundries may also offer design rules or automated mask checks.
about them. This process will go most smoothly if your documentation is complete and your company’s process engineers are available for multiple meetings with the foundry’s team, ideally with at least one being held in person. Even with a detailed POR to provide the foundry, if you were to simply “throw it over the fence” to the foundry, do not expect very good results. Tech transfer is far more involved than simply uploading documents. Your engineers should be prepared to meet with the foundry on a regular basis throughout the entire foundry feasibility stage, and beyond, until production is reached. It can be extremely helpful to create and collectively agree upon with the foundry team a plan that outlines the transfer and first processing run, what needs to be done and by when, where each step will take place, and who will be responsible.

**Translating an Advanced Prototype Runsheet for a Different Toolset**

Once the foundry is up to speed on your POR, the next step will be to work with the foundry’s engineers to translate your advanced prototype runsheet to their toolset. Your runsheet was developed on your development fab’s set of tools, and it is highly unlikely the foundry has the exact same makes and models of equipment. The foundry engineers must therefore figure out a way to get the same films, stresses, material qualities, and features from their own set of tools. Even if the foundry happens to have the same model tools that you used in development, you should be prepared for the possibility that the tools might give slightly different results. Just because your process worked perfectly on your tool does not mean that the foundry will be able to duplicate the process on their tool the first time through. Understanding
what films, materials, and processes could be substituted if the process cannot be exactly duplicated can also help with the transfer process.

A key part of the transfer and translation process is also developing the acceptance, or pass/fail, criteria for each step of the wafer fabrication process. Identify which key specifications are design- or process-based and establish how they will be confirmed. If there is no clear division of labor, then you may need to handle it or work with the foundry to do it together.

The foundry’s operators eventually need a set of criteria against which to judge whether the process was correctly executed or not. At this stage, you must be quantitative and specific about what is essential in each process step. For example, it is not enough to specify the alignment between a piezoresistor element and the edge of a membrane in a silicon pressure sensor by the mask layout alone. You also need to provide an acceptable alignment tolerance (e.g., ±3 µm). Another example for a pressure sensor would be the tolerance on the bridge resistance of the sensor. Specifying a tolerance of ±1% versus ±10% could be the difference between giving the foundry a difficult process requiring many short loops to stabilize versus one that is easily achieved. Process tolerance values may be based on your testing of advanced prototypes, or on prior modeling, and they all must be measurable by the foundry.

Providing the foundry with this specific process acceptance data will dramatically increase the odds of successful process transfer and of achieving working devices at the end of the foundry’s feasibility stage. Keep in mind that at a foundry, the process engineers may not look at your wafer at every step and cannot make changes on the fly to adapt to unexpected results. If you feel anxious that your wafers really need to be closely monitored by a foundry process engineer, then your product may not be truly ready for foundry production (Review the readiness criteria in Chap. 17).

Wherever there might be missing information between process specifications and acceptance criteria, then short loops, wafer splits, or staging can be used effectively to discover that information. (Please refer to Chap. 15 for more information on these fabrication risk mitigation methods.) Identifying this vital information and taking time to discuss it with the foundry engineers will help you to capture maximum value for the money spent at the foundry and will set both parties up for a successful start to a long relationship.

**Transferring Photomask Layout Data**

The bare minimum mask documentation you would prepare for the foundry is a mask layout file and a list of all of the mask layers. Even the simplest MEMS mask layout design benefits from additional documentation describing key mask features, the alignment strategy, and the mask digitization information (data digitized dark or clear, polarity). Please see Chaps. 11 and 16 for some tips for managing and documenting the mask layout.
Automated design rule checks (DRC) for MEMS mask layouts usually do not happen with a custom fabrication process. If you happen to be using an established process or a foundry platform process, then your layout may be subject to the foundry’s DRC. If you are using a platform process at a foundry, design rules should have been provided to you by the foundry. You will need to confirm that your mask layout conforms to them and to resolve any discrepancies before the foundry will accept your mask data for production.

Whether using a custom or a platform process, you will likely only need to deliver the unit cell of your device’s layout, which the foundry’s mask engineer will then use to populate a photomask reticle and/or wafer layout, in the case of contact lithography. Even with a well-defined and documented mask layout file, the data delivery process to the foundry can be more time-consuming than you might expect. You will need to learn the foundry’s mask data submission process, which is different for each foundry. Then the foundry will need to add its own alignment marks and process control monitor test structures (PCM). Because of this added data, you may never be allowed to see the final mask file. It is now considered property of the foundry because it may contain the foundry’s proprietary information.

The foundry will, however, send some form of the final mask layout as a “proof sheet” for you to double-check. This is a very important step! Do not blindly assume that the mask data has been correctly processed, no matter how many conversations you have had. You may need to go back and forth with the foundry’s mask engineer a few times before the mask layout can be finalized. It can be especially helpful to create a document outlining the photomask data file transfer process and the responsible parties for each step (your company or the foundry) because so much information is being transferred back and forth. If a mask revision would ever be required at a later date, then this process will need to be repeated.

When the mask data transfer is finally complete, we recommend that you document what you sent to foundry and why, for your own internal records as well as to assist future photomask layout data submissions.

**Monitoring the Foundry Feasibility Stage**

In the foundry feasibility stage, the purpose of the wafer runs is for the foundry to translate and to replicate your advanced prototype process on its own tools. These first few runs are for learning and transfer of information, not about fabricating working product. It is not unusual for wafers from these first runs to be only partially finished or to not yield any functional devices at all. If you find yourself in this situation, you can take a little comfort in knowing it is not the first time it has happened when transferring MEMS technology.

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2Your company executives and investors, however, will likely be putting pressure on everyone to deliver working product out of these initial runs. Educating them on the foundry stages of development (Chap. 3) can help to adjust their expectations.
This can be a very high-pressure period of time for any company, but especially for start-ups, whose access to more funding may depend entirely on its success. While you are in this critical learning phase of the transfer, it is essential to stay in close touch with the foundry team, to increase the chances of a successful transfer. Some good practices include:

- Establish the main points of contact at the foundry and at your company.
- Set up biweekly meetings between the teams.
- Have the foundry provide a visual report on wafer progress, with pictures, data, etc. for at least the first wafer lot run. Reporting during later runs, once the process is stable, can become more administrative.
- Have a project manager and MEMS expert within your company on call, in case any issues arise which need prompt attention.

During the first runs, you will need to let the foundry do its job, but do not expect them to do all of the work to monitor the project results. Without regular input from you, they may not have the all information they need to successfully complete the first wafer runs.

The Foundry Engineers Are Your Partners Now

The foundry engineers are your expert collaborators now, and if you treat them as part of your development team, you will reap the most benefits from the relationship. The foundry team brings a large body of knowledge and experience from having transitioned other clients’ products to high-volume manufacturing. They have a distinct skill set on developing processes for stable production, and know what is possible or not possible on their tools. The foundry team wants you to be successful, because their business model and long-term profitability depends on reaching and sustaining high-volume production of your product. They are not in this business to do endless research and development, so if the foundry team is suggesting short loops or other work, such as a design modification, it is because they are trying to reduce long-term fabrication risks and to improve product yield.

Conversely, they should be treating your team with respect, because your team is the expert on your novel product design. Your advanced prototyping experience can help inform the foundry on how to best mitigate processing risks (see Chap. 15). Any conflicts with the foundry team must be resolved early on; any serious or irrecconcilable personality clashes might need to be resolved with reassignment of personnel.

If you happen to discover any gaps between what the foundry’s sales team promised you and what the foundry process engineers state is possible, these must be resolved immediately. If you detect that the sales team has dramatically oversold the foundry’s capability, for example, claiming expertise with a process that the foundry’s engineers are treating more like a new experiment, immediately bring this to their attention and work to get it resolved. If the foundry cannot quickly close the
gap in process expertise, consider cutting your losses while still early in the transfer and switch foundries right away.

During the transfer phase, your team should take the time to visit the foundry in person again and make the effort to develop a professional rapport with the foundry team. If you only have funds to visit once a year, go when you are working on the technology transfer and process documentation. You should be meeting with the foundry engineers and project manager assigned to your company, and if possible, meet the operators on the key tools for your process. (This may not be possible at high-volume foundries.)

“Golden Wafers” and Murphy’s Law

Sometimes, early in development, a “golden wafer” appears. A golden wafer is one that has devices with the exact performance you were hoping for, and/or has exceptionally high yield. (Often, it looks beautiful and flawless, too. Be sure to take lots of pictures of it for your marketing team!) Once you see a golden wafer, it is only human nature that you will expect all future wafers to also be golden, and thereby set yourself up for some potentially serious disappointment.

A typical story that we have often seen in our business: a golden wafer appeared in the last advanced prototype batch at the development foundry, and as a result, everyone felt that, at last, it was the right moment to transition to a production foundry. Everyone’s expectations were set high that the foundry would immediately be able to replicate many more wafers with the same golden results. Then the first run in the foundry feasibility stage does not yield any golden wafers; then neither does the second. By this time, the customer would often be quite impatient and even angry—where are the working devices?

A golden wafer that appears in development can be a mirage—the appearance that you have figured out the perfect process—when in reality, it results from a lucky set of circumstances which you do not quite know or understand. If you are lucky enough to see a golden wafer, treat it as merely an existence proof, evidence that it is possible to get great devices. It will take a lot of hard work by the foundry to then tune and replicate the exact set of process circumstances which consistently yields golden wafers. The foundry’s methodology for development (summarized in Chap. 3) exists to systematically work through all the process variables, using methods such as design of experiments, 6-sigma, and response surface characterization, to create a stable process that will make golden wafers by the thousands. This takes time.

Murphy’s law (if it can go wrong, it will) applies in MEMS at every stage of the product development. It never ceases to amaze us how even seemingly simple processes can go very wrong. All your hard work on the advanced prototypes and during the foundry transfer helps to minimize the risk that Murphy will appear, but keep an eye out for him anyway. If you did not know if your process would work well the first time, then the foundry will not either. Be prepared to shoulder some of
the weight of problem solving with your foundry partner. Everyone feels better about working together to get through tough points. It sends the right message that you are indeed a team.

**Process Monitoring**

Process monitoring is the task of regular measurement and data tracking of the wafer process at the foundry. Examples include measuring furnace temperatures, film thicknesses, and device feature dimensions. The foundry is typically well aware of which parameters are best monitored in order to monitor the health of each tool and each process step. You, on the other hand, understand your device best. As a result, work together with the foundry to establish a process monitoring plan. This may include designing process control monitor test structures with the foundry that address processes that are critical for your device. During the first run of the foundry feasibility stage, you may be able to review the process monitoring data with the foundry and make sure that the process is properly monitored within the correct limits.

Your ability to review all process monitoring data from every run often depends on the size of the foundry. This request would add to the foundry’s burden and might slow down wafer processing. Moreover, the foundry is the responsible party for proper function of its tools. It can be argued that if you were to get too involved, you could become a partially responsible party if anything were to go wrong. Instead of reviewing all process monitoring data, you might request that the data specific to your runs be saved so that it could be reviewed at a later time, if and when a problem occurs.

Once a new process has been established and stabilized, routine process monitoring data would continue to be watched by the foundry personnel, but it would not usually be reviewed by you. If and when a tool performance problem emerges, the foundry would likely react to it and solve it without informing you.

**Moving on to Pilot Production**

Once the foundry completes the feasibility stage runs successfully, it will have met its own internal quality criteria for moving on to the next stage, pilot production. When you have reached this stage, the technology transfer has been completed, and the responsibility for the process is in the hands of the foundry going forward.

During the foundry pilot production stage, and later during production, your engineering team’s interaction with the foundry technical staff will become much less frequent, perhaps even shrinking to an annual review. A very stable, long running production process may eventually be managed only by purchasing personnel at your company, who interact with an account manager counterpart at the foundry.
Managing Ongoing Risks

Even while foundry production is proceeding smoothly, any number of internal or exogenous risks are always present. Here are a few which deserve your attention.

Cost and Availability of Materials

Although the element silicon is abundant in the Earth’s crust, the number of factories on our planet that can purify silicon ore and form single crystal ingots is limited. During economic boom times in the semiconductor and solar power industries, demand for silicon goes up due to the fixed capacity for processing silicon, causing the price for silicon to go up as well.

These market dynamics were especially acute during a boom period in the solar panel industry, 2006–2010, during which the price of raw silicon rose more than tenfold as demand far outstripped global processing capacity. [1]

Yet another group of factories perform wafering, the process of slicing single crystal silicon ingots into wafers and polishing them. Many MEMS devices employ silicon-on-insulator (SOI) wafers, which are also commonly used in the semiconductor industry. Manufacturing SOI wafers requires special equipment and processes and only a limited number of factories on the planet can produce quality SOI wafers. During 2017–2018, when there was heavy demand for SOI wafers due to a boom in the semiconductor market, the lead time for SOI wafers increased dramatically. In our business, we experienced an increase in lead times for custom SOI wafers, from the typical 4–6 weeks to 6–12 months.

The semiconductor and solar power industries, behemoths compared to the MEMS industry, drive the supply and demand cycles for silicon wafers. A MEMS product company and its foundry partner should carefully track market changes in the cost and availability of the wafer types needed for manufacturing the MEMS product. Foundries will often build up wafer inventory to buffer against anticipated market changes. Increasing wafer inventory ties up capital, so thoughtful financial planning and analysis with inputs from both partners is needed to make solid strategic decisions.

Facility Damage

Any number of potential damage events can take a foundry offline for days to years or more. The most common foundry disruptions occur from minor incidents, such as flooding from a burst pipe or perhaps a sudden tool failure, which can disrupt production for hours to days, and rarely for weeks.

Fire is a more serious risk because even minor fires can result in long downtimes, weeks to months, due to the need for cleanup from smoke damage and particles. Recovery from a major fire, as occurred in a fab owned by GE Druck in the UK in 2014, can take over a year [2, 3].
Less frequent but potentially catastrophic risks, such as earthquake, typhoon, and particulates from wildfires or volcanoes, exist at many fab and vendor locations, particularly those located along the Pacific Rim. Foundries in developing countries may also be at risk for interruption or damage from intermittent power outages.

More recently, in 2020, the global pandemic of COVID-19 affected foundry performance worldwide. While most foundries kept operating as essential businesses, the need for “social distancing” within the facility reduced the number of people who could be working at one time, thereby reducing fab capacity and wafer throughput.

MEMS product companies should continually evaluate their entire supply chain, not just their foundry partner, for robustness and then make sure that appropriate redundancies or back-up manufacturing plans exist. For products such as critical medical equipment components, it would be wise to identify second source vendors in a completely different geographic location in order to ensure business continuity in the event of a regional disruption.

International Business Issues

In addition to potential language barriers and working across different time zones, doing business with international suppliers carries a few risks that can be safely managed if handled attentively. One common risk is foreign currency fluctuation, especially for vendor jobs which might span months or years between initial quote to final payment. Fortunately, many vendors in the semiconductor and MEMS industries are accustomed to doing business internationally and are usually willing to quote and accept payment in your company’s home currency in order to eliminate your risk of price change due to currency fluctuation.

Changing political positions on international trade agreements, import tariffs, and worker visas also have significant effects on the practicality and cost of doing business with a foreign vendor. Any change in import/export duties or new tariffs could make a once economical cross-border business totally impractical. Companies doing significant amounts of international outsourcing should consider adding domestic or third country vendors to their supply chain in order to hedge against sudden, unfavorable changes in trade policies.

Actively Manage Foundry and Vendor Relationships for Best Long-Term Results

Manufacturing a MEMS product is a complex undertaking involving hundreds to thousands of people, advanced technology and facilities, multiple disciplines, and a supply chain spanning the globe. Business and operations leaders, even those within vertically integrated companies, need to devote a portion of their attention to monitoring and nurturing the complex ecosystem upon which their company’s production and success depends.
First and foremost, successful supply chain management requires tending to the human relationships, which are so easily and often overlooked. Until we reach the point where robots run factories and an artificial intelligence can make nuanced judgment calls, the strength of a company’s supply chain ultimately depends on the strength of the human relationships between the entities. Investing time in getting to know the leaders of key supply companies, and in understanding their business’s challenges and outlook, will help both parties when the inevitable problem or interruption occurs. Trust between people remains an incredibly valuable asset in the technology business.

It is also important to share business information and outlook, for mutual advance planning. Practically speaking, the foundry, and all the vendors in your supply chain, are your company’s business partners. The foundry, to a large extent, is an investor in your company. Treat them with the same respect and openness as you would your other business partners or investors. You are in it together for the long haul.

Summary

Preparing for tech transfer starts with clear, concise documentation of your MEMS device layout and process flow. Ideally, your engineering team and the foundry team will meet in person to review the documentation and answer questions in real time. When the foundry has transferred the layout and process flow to their tool set, you will need to review their file for accuracy—do not assume that your data has been interpreted correctly. During the feasibility stage, meet with the foundry on a regular basis to discuss progress and issues as they arise. The foundry, with your input, will determine when the project is ready to move onto pilot production. These two stages can take 1–2 years. With your diligent preparation and with attention by the foundry, you can create the best conditions for the foundry production to run smoothly.

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