Use of Failure Modes and Effects Analysis (FMEA) Methodology in Evaluation of Process Transfer of Ohmic Liftoff from Low-Pressure-Solvent to High-Pressure-NMP Liftoff

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ABSTRACT

Liftoff metallization processes are widely used in the processing of GaAs and other III-V compound-semiconductor integrated circuits and FET products. The primary application is following electron-beam evaporation of an interconnect-metal film where the liftoff is usually accomplished by one or more solvent, tape, or high-pressure spray methods. This paper demonstrates the use of the Failure Modes and Effects Analysis (FMEA) method for assessing the requirements and risks associated with a process change. In this particular example, the original process method in use for comparison as the baseline was a low-pressure acetone liftoff of a multilayer ohmic contact film. Yield difficulties corresponding to incomplete liftoff had been experienced when using the baseline low-pressure method and the objective was to transfer the process to a high pressure spray tool so that thorough and efficient liftoff could be sustained.

The use of an FMEA approach wherein the modes of potential failure are carefully evaluated and subjected to experimentation and control was highly beneficial in organizing the improvement effort. Details of failure modes and solutions are presented.

INTRODUCTION

Failure Modes and Effects Analysis (FMEA) is a widely used evaluation method for both the automobile industry and other organizations employing Six Sigma techniques and problem solving approaches. Properly applied, an FMEA can be a useful tool in organizing and pinpointing areas of highest concern and then for focusing effort and documenting results. The basic steps are to identify the root process, list potential problems that could occur, rate the failure mode for severity, occurrence, and detectibility, and then derive a Risk Priority Number (RPN) which can direct design or improvement effort to the areas of greatest concern. Actions are then undertaken to reduce the risk presented by the failure mode.

For the case at hand, an effort was underway to transfer an ohmic-metal liftoff process from a low-pressure solvent tool system utilizing acetone and isopropanol to a newer tool using heated NMP and high-pressure (HP) pumps. Recirculating the NMP and using high-pressure spray was expected to both greatly improve the 1st-pass liftoff success and also reduce chemical consumption. But the method and chemical employed were also radically different than the method in production for many years. As a consequence there was a need to be sure that all appropriate failure modes were considered and thoroughly investigated.

Figure 1 is a truncated version of the FMEA developed for this process transfer. The far right-hand column contains the derived RPN number with high numbers expressing areas of most significant concern. In preparing an FMEA, we have found it useful to carefully consider not just the column title, but also the underlying question relating to the entries. Thus, for example, when evaluating the "POTENTIAL FAILURE EFFECT" we are really asking not just what happens during the processing, but also how the failure effect can ripple through to the end user.

Process or Product Name:	Ohmic Liftoff (4030) in the Karl Suss HP spray tool	Prepared by: **Stephan W. Kittinger**
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What is the process step	What is the Key Process Input?	In what ways does the Key Input go wrong?	What is the impact on the Key Output Variables (Customer Requirements) or internal requirements?	How Severe is the effect to the cusotmer?	What causes the Key Input to go wrong?	How often does cause or FM occur?	What are the existing controls and procedures (inspection and test) that prevent eith the **cause or the Failure Mode?** Should include an SOP number.	How well can you detect cause or FM?	Risk Priority Number
Process Step	**Key Process Input**	**Potential Failure Mode**	**Potential Failure Effects**	**SEV**	**Potential Causes**	**OCC**	**Current Controls**	**DET**	**RPN**
Ohmic Liftoff	NMP dispense to wafer	**Trenching**	RcN high (4350&8350)	9	Degraded / Contaminated NMP	2	4350 & 8350 test to validate RcN	2	36

Figure 1: FMEA for ohmic liftoff in HP tool

Figure 2 shows examples of how different failure modes could occur and the consequence of each particular mode. As an example, ohmic trenching where the pad contacts the GaAs is a failure mode that could result in high ohmic contact resistance (Rcn) if the NMP dispense to the wafer is contaminated.

Key Process Input	Potential Failure Mode	Potential Failure Effects
NMP dispense to wafer	**Trenching**	RcN high (4350&8350)
NMP solvent	**GAT or OHMIC metal attack**	Elevated TFR rsh, degraded devices, poor GAT control
HP Pump age	**Extraneous Ohmic Mtl.**	Shorts
NMP pressure	**Lifted Ohmic Mtl.**	Ckt functionality
NMP Side spray despense pressure	**Scraped Ohmic Mtl.**	Metallization deformities
NMP supply	**Surface staining**	Visual abnormalities

Figure 2: FMEA Potential Failure Modes

DISCUSSION

Utilizing the FMEA methodology to evaluate an entirely different ohmic liftoff process proved to be an invaluable approach for identifying ALL of the different scenarios that could potentially cause failures using the new high pressure ohmic-liftoff process. Making use of the new liftoff tool and generating the process FMEA, we were able to quickly learn that there were numerous failure modes that could potentially occur, jeopardizing product quality and performance. In the past when generating FMEAs for new processes, we frequently found ourselves struggling to fill out the FMEA form due to not having a clear understanding of what information was to be placed into the specific columns.

We found that developing the FMEA from the "inside out" was the simplest and most methodical approach when generating the failure analysis tool for our ohmic liftoff improvement. As our multifunctional group convened, we first identified the "POTENTIAL FAILURE MODES" that could occur with the new process. We next moved to the "KEY PROCESS INPUT" column where we identified the many different inputs that could generate the "POTENTIAL FAILURE MODE". Utilizing this approach, we were tremendously surprised at just how many of the "PROCESS INPUTS" could potentially generate a single failure mode. After identifying the "PROCESS INPUTS", we then completed the columns for the "POTENTIAL FAILURE EFFECTS" and the "POTENTIAL CAUSES" for the failure mode.

Figure 3 illustrates the many different possible inputs and causes that could potentially generate the single failure mode of "Extraneous Ohmic Metal".

Process Step	Key Process Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN
Ohmic Liftoff	HP Pump age	**Extraneous Ohmic Mtl.**	Shorts	10	Pump seizes	3	4030 & 9400 visual inspection	8	240
Ohmic Liftoff	NMP pressure	**Extraneous Ohmic Mtl.**	Shorts	10	Pressure regulation problem	5	4030 & 9400 visual inspection	8	400
Ohmic Liftoff	Solenoid signal	**Extraneous Ohmic Mtl.**	Shorts	10	Dispense valve failure	2	4030 & 9400 visual inspection	8	160
Ohmic Liftoff	Maintenance to chmber	**Extraneous Ohmic Mtl.**	Shorts	10	Nozzle moved out of position	4	4030 & 9400 visual inspection	8	320
Ohmic Liftoff	Solvent filtration	**Extraneous Ohmic Mtl.**	Shorts	10	Clogged nozzle	2	4030 & 9400 visual inspection	8	160
Ohmic Liftoff	Solvent filtration	**Extraneous Ohmic Mtl.**	Shorts	10	Clogged filters (1.0, 0.1, paper filter)	3	4030 & 9400 visual inspection	8	240
Ohmic Liftoff	Operator	**Extraneous Ohmic Mtl.**	Shorts	10	Wrong Liftoff process used	4	4030 & 9400 visual inspection	8	320

Figure 3: A single Failure Mode stemmed from numerous Key Process Inputs and Potential Causes of failure.

After generating what we believed was an extremely thorough FMEA for the new HP ohmic liftoff process, we found ourselves experiencing difficulty rating the Severity, Occurrence, and Detection for each of the failure modes. This spurred dialogue amongst the group and we determined that the Ratings Guide that we were given was tailored more for Circuit Design and not Process Manufacturing. We then consulted management and our Quality department whereupon we decided to develop an FMEA Ratings Guide tailored for Process/Manufacturing improvement efforts. See Figure 4 below showing the new Ratings Guide sheet that we now use for evaluating new fabrication processes in Wafer Fab.

Engineering judgement or other expert assessment is often needed to assign accurate values but this is a necessary task in order to make sure that the proper failure modes are targeted for attention. After implementing our new ratings guide sheet for process manufacturing FMEA's, we were in full agreement about the ratings obtained for Severity, Occurrence, and Detection in determining the Risk Priority Number (RPN) for the failure modes that could occur with the new HP liftoff process. After identifying the highest-risk failure modes, we went on to perform appropriate evaluations for the new process and institute control methods which would be regularly checked to validate that the process is operating properly.

RESULTS

After completion of the FMEA for the new HP ohmic liftoff process, we identified the failure modes having the highest RPNs. These were the failure modes that warranted extensive evaluations and trials before the process could be released for production. We now discuss in some detail two of the high-RPN failure modes that were identified and evaluated; trenching and extraneous-ohmic-metal failure modes.

FMEA Coding Guide for Wafer Fab Operations 902053 --

Severity of Effect (seriousness of impact wrt customer– internal or external as the case may be)

Severity	Description	Rank
Extreme	Products fail prematurely in the field greater then 50 PPM	10
Severe	Products fail prematurely in the field less the 50 PPM	9
Very High	Product fails at final test at greater than normal loss %	8
High	Wafer failures at 9400	7
Moderate	Wafer failures at EOP	6
Low	Wafer failures mid process	5
Very Low	Non-standard rework	4
Minor	Rework greater then 15 min	3
Very Minor	Rework less than 15 min	2
None	No effect	1

Occurrence Rate (frequency at which the cause of the is likely to occur)

Probability of Occurrence	Frequency Related to Lot Processing	Rate	Rank
Certain	Every lot	1 in 1	10
Extremely High	Every other lot	1 in 2	9
Very High	3 lots per day	1 in 3	8
High	2 lots per week	1 in 10	7
Moderate	Once per week	1 in 20	6
Low	Once per month	1 in 80	5
Very Low	Once in 6 months	1 in 400	4
Minor	Once in 2 years	1 in 2000	3
Very Minor	Once per 10 years	1 in 10,000	2
Remote	*Maybe* once per career	1 in 100,000	1

Detection Effectivity (likelihood the effect [defect] will be caught before wafers or product get to the customer – cause and/or failure mode detection is better than effect detection)

Detection Probability	Defect Detection Capability or Process Control	Rank
Zero	No method known to detect defective product	10
Almost Zero	Very unlikely that current inspection/control methods will detect effect/defect	9
Very Low	Current inspection/control methods will seldom detect effect/defect	8
Low	Current methods detect effect/defect occasionally (about 25% of the time)	7
Moderate	Current controls can detect the effect/defect about 50% of the time	6
Moderately High	Current controls can detect the effect/defect about 75% of the time	5
High	Current controls can detect the effect/defect about 90% of the time	4
Very High	Current controls can detect the effect/defect about 95% of the time	3
Almost Certain	Current controls can detect the effect/defect about 99% of the time	2
Certain	Current controls always detect the effect/defect	1

Process Controls (defect and failure detection methods)

Control Type (purpose of control)	Rank
Detects the failure mode but not the specific cause.	3
Detects the cause/mechanism; leads directly to corrective action.	2
Prevents the cause/mechanism from occurring.	1

Figure 4: Revised Ratings guide for Wafer Fab FMEAs

During early trials with this new HP liftoff process, we did encounter a high RPN failure mode identified in the FMEA as "trenching along the ohmic contact region" which can result in an increase in ohmic contact resistance. We were able to identify the root cause for this failure mode and eliminate this problem during the initial evaluation of the process.

Figure 5 below illustrates some initial results obtained visually and electrically while performing the ohmic level liftoff using the new HP spray tool.

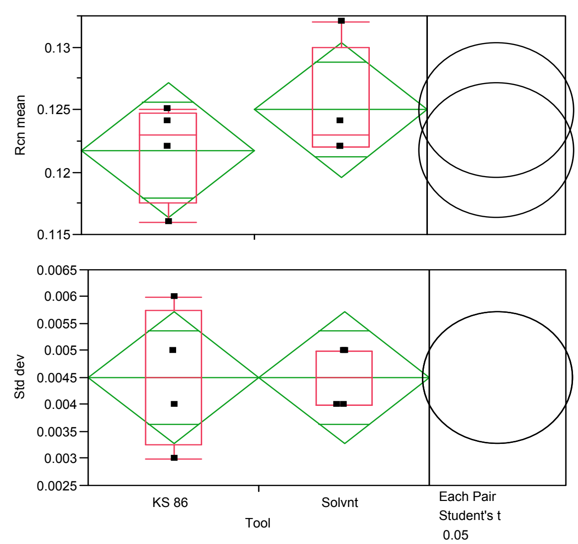
After eliminating the cause for the trenching failure mode, we ran split lots between the standard low pressure (LP) solvent liftoff process and the new HP ohmic liftoff process on ALL process families that we have in the Roanoke wafer fab. Illustrated in Figure 6 is the result of a single split lot for which we evaluated ohmic contact resistance results from the new HP liftoff process. Both wafer means and standard deviations are well aligned between the old and new process indicating that the new process produces equivalent results for these important parameters.

Wafer #	Recipe	Visual results of HP liftoff	Rcn mean	Rcn sd
2	9	3% metal remaining in dropout and major flat region	0.206	0.033
4	10	10% metal remaining in sweet spot	0.172	0.009
6	85	10% metal remaining in sweet spot	0.177	0.012
8	85	10% metal remaining in sweet spot	0.167	0.013
10	85	3% meal remaining in the sweet spot	0.175	0.007
12	85	<1% amount of metal remaining. Only one small spot at dropout	0.21	0.011

Figure 5: Elevated ohmic contact resistance (Rcn) due to trenching along ohmics: identified from the FMEA as having a high Risk Potential.

A second high RPN failure mode is extraneous ohmic metal or incomplete liftoff. In our standard process, incomplete ohmic level liftoff was a issue that we had to deal with because the ohmic metal film is embedded within a dielectric passivation layer. Furthermore, circuit yield analysis showed that defects originating from the ohmic liftoff process were a leading cause for failure. The labor intensive reworks and reduced yields elevated the priority for attention and this became a major driving force behind conversion from an exclusively low pressure solvent liftoff method to a high pressure liftoff system.

Figure 6: Ohmic contact resistance comparison: Contact resistance mean and standard deviation for new HP NMP vs. previous Solvent liftoff



Tight pitched "Ohm-Ohm" liftoff
Process "n" embedded ohmic liftoff

COBHAM

RF19XX-E03

EMBEDDED OHMIC LIFTOFF IN DIELECTRIC FILM
EVEN WAFERS THROUGH NEW HP OHMIC LIFTOFF
ODD WAFERS THROUGH STD SOLVENT LIFTOFF

OHM to OHM SHORTS THROUGH FULL SITE TESTING

WAFERS	4030 LIFTOFF	SITE FAILURES EXCEEDING 1e-3 CURRENT COMPLIANCE	% SITE FAILURES	PERCENT SITE FAILURES FROM LIFTOFF
1	STD	9/41	22.0	**49.60%**
3	STD	27/41	65.9	
5	STD	25/41	61.0	
7	STD	X	X	
2	NEW HP LIFTOFF	0/41	0.0	**0.60%**
4	NEW HP LIFTOFF	0/41	0.0	
6	NEW HP LIFTOFF	0/41	0.0	
8	NEW HP LIFTOFF	1/41	2.4	

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Figure 7: Electrical test results showing the OHMIC liftoff improvement using the new liftoff process.

Figure 7 illustrates the liftoff improvement results between our previously-used LP solvent liftoff vs. the new HP ohmic liftoff. In this example, a split lot was run using both our standard process and a recipe under evaluation for the new process on the HP liftoff tool. The dramatic difference in the electrical compliance results is further

After complete process evaluations were made on the new HP ohmic liftoff process, the final step was to implement a Control Plan to insure that the Key Process Inputs would be properly documented, controlled, and monitored in order to prevent the failure modes identified in the FMEA from ever occurring. Figure 8 illustrates a portion of the listed control items that are outlined in our Control Plan for the new HP ohmic liftoff process.

CONTROL PLAN - update		No.	Process	Control Method	Reaction Plan
Process Name/ Operation Description	Machine/ Device, Jig, Tools for Mfg.				
OHMIC METAL LIFTOFF	KARL SUSS M6000L	1	NMP Dispense Pressure	Operations - to be monitored for 1st wafer in each cassette ran	Notify EMG
OHMIC METAL LIFTOFF	KARL SUSS M6000L	2	HP Nozzle height	Checked as needed due to damage, replacement, equip. malfunction	Notify EMG
OHMIC METAL LIFTOFF	KARL SUSS M6000L	3	NMP HP dispense temp.	tool controlled	Notify EMG
OHMIC METAL LIFTOFF	KARL SUSS M6000L	4	NMP recycled temp	tool controlled	Notify EMG
OHMIC METAL LIFTOFF	KARL SUSS M6000L	5	Heating Julabo	Operations - To be checked per shift	Notify EMG

Figure 8: Excerpt from Control Plan for the HP ohmic liftoff process.

SUMMARY AND CONCLUSIONS

Introducing a change in manufacturing processes presents a potential opportunity for unexpected yield-loss and failure modes that have never been observed with prior processes. It is vitally important that a formal methodology be followed in order to evaluate all risks associated with a process change. We have found that by using Failure Modes and Effects Analysis (FMEA) carefully and methodically we can successfully identify the most significant risks associated with a change to the manufacturing process. In this example, the FMEA methodology was applied to evaluation and implementation of an improved process for ohmic liftoff. The FMEA process pointed to aspects of the new process that had potential for high risk, with particular concern regarding long-term reliability of the product. Use of the FMEA tool helped avoid pitfalls that could have otherwise resulted in premature and inadequate implementation of a new, improved process. By using the FMEA tool, a new process for ohmic liftoff, which is truly improved and proven to be without risk, is now in place without many of the manufacturability problems inherent in the old process.

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