A study on manufacturing methods for flexible microelectronics

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Abstract

Various manufacturing methods are analyzed by using manufacturing metrics to validate which method would be applicable to flexible microelectronics. Among others, Roll-to-Roll method is revealed to inherently have an excessive WIP resulting in long cycle time and limited diversity as well as low equipment efficiency.

1. Introduction

Various manufacturing methods for flexible substrate based microelectronics (hereinafter abbreviated as 'flexible microelectronics') can be categorized as shown in Figure 1.

Every method incorporates a number of photomask steps to manufacture a device such as a (either amorphous- or low temperature poly-) Si based as well as organic semiconductor based active matrix addressing type flexible display.

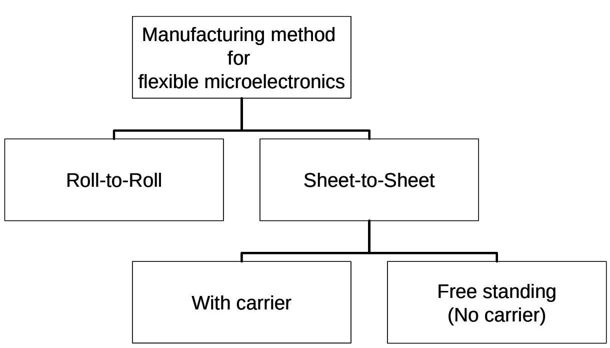

Figure 1 Various manufacturing methods for flexible microelectronics

Among others, a Roll-to-Roll ('R2R') manufacturing method is often considered to be a 'logical' step for mass production of flexible microelectronics rather than a Sheet-to-Sheet ('S2S') method, in which devices are being processed in a sheet form.

This paper will aim to analyze differences in manufacturing methods for flexible microelectronics, namely between a R2R and a S2S method, by using manufacturing metrics.

2. Analysis

1) WIP and Cycle time

The following metrics are key to analyze a manufacturing method:

- Cycle time (CT):
  The time taken between lot release (i.e. material-in) and process completion (i.e. product-out).

- Throughput (TH):
  The average output of a production process (machine, line or plant) per unit time (e.g. parts per hour ('UPH'))

- Work In Progress / Work In Process (WIP):
  The inventory between the start and the end points of a product routing

Little's Law [1] describes the relationship among these parameters as stated in:

$$CT = \frac{WIP}{TH} \quad (1)$$

Generally speaking, a manufacturing process of flexible microelectronics consists of a number of photo-mask steps as shown in Figure 2. Each photo-mask step consists of various process steps such as deposition, cleaning, etching and so forth as shown in Figure 3.

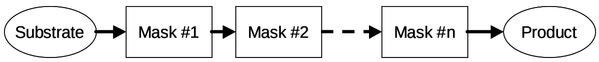

Figure 2 Typical process flow of microelectronics

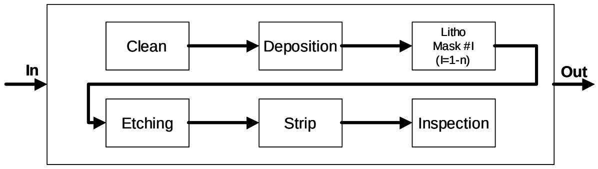

Figure 3 Typical process flow within one mask step

In case a R2R method is applied on such process steps, normally it can be done in a discrete way as indicated in Figure 4 due to the difference in term of process environment, i.e. either in vacuum or in the air, as well as either dry or wet.

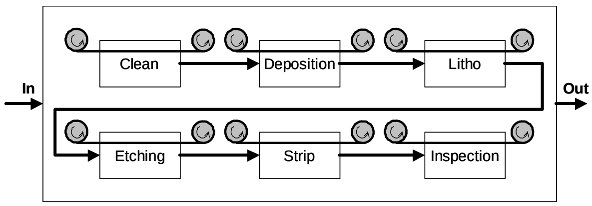

Figure 4 R2R manufacturing method in a discrete way

The attempt can be made to estimate cycle time in case a R2R method is applied on a microelectronics manufacturing process in a discrete way under the following conditions:

- Length of a roll = 1000 meter
- Width of a roll = 0.6 meter
- Number of photo-mask steps = 5
- Number of process steps per photo-mask step = 6

The minimum WIP of the manufacturing process can be derived as:

$$WIP = 1000 \times 5 \times 6 = 30000\,(meter) \quad (2)$$

Assuming that Throughput of the process, i.e. process speed, is 1 meter per minute, the theoretical Cycle time of the process, i.e. the minimum cycle time with no waiting time in between processes, will be:

$$CT = 30000/1 = 30000\,(\text{min}) \approx 21\,(days) \quad (3)$$

In the same context, the cycle time can be estimated when a S2S method is applied under the following conditions. In this case, practically a cassette will be used as a media to store sheets for loading and unloading a sheet to/from a processing machine:

- Length of a sheet = 0.5 meter
- Width of a sheet = 0.6 meter
- Number of sheets per cassette = 20
- Number of photo-mask steps = 5
- Number of process steps per photo-mask step = 6

The minimum WIP of the manufacturing process can be derived as:

$$WIP = 20 \times 5 \times 6 = 600\,(sheets) \quad (4)$$

Assuming that Throughput of the process is 2 sheets per minute such as in major Gen #3 TFT LCD factories, which is equivalent to the process speed of 1 meter per minute in case of R2R method, the theoretical Cycle time of the process will be:

$$CT = 600/2 = 300\,(\text{min}) \approx 0.21\,(days) \quad (5)$$

In comparison with a S2S method, it becomes clear that a R2R method can generate a huge excessive WIP and it will lead to the following consequences:

- As derived by Little's law, an excessive WIP leads to a long cycle time, which will directly link to the long learning cycle. The long learning time implies that it will take at the least the sum of the cycle time of all processes to see an effect of any change in process/technology in manufacturing process after it is implemented.
- Long cycle time will result in less diversity in terms of the number of product types in production. Unlike a S2S method, a R2R manufacturing process would be dedicated to only few product types since it cannot respond to immediate product change due to the materials, which are already halfway processed in the line as WIP.

- The risk to obsolete WIP due to 'wrong' processing always exists in any manufacturing method. In worst case, when it is revealed at the very last step that materials are 'wrongly' processed, the total cost of obsolescence will be equivalent to the total sum of WIP within the whole manufacturing process. An excessive WIP thereby could result in a huge amount of obsolescence.

2) Availability and Reliability

The ease with respect to integration of various process steps as shown in Figure 5 has often been discussed as one of the advantageous features of a R2R method in case it is applied to manufacturing flexible microelectronics.

When more than 2 process steps are integrated into one system however, both the availability and the reliability of the total system must be cautiously considered.

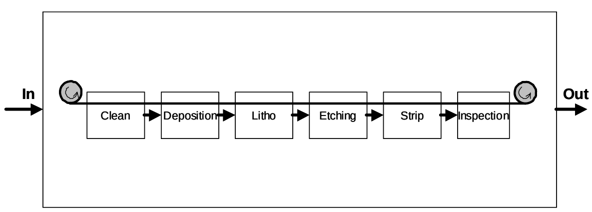

Figure 5 R2R manufacturing method in an integrated way

The availability is the ratio of how much a machine will be available by taking its random outages into account, i.e. the fraction of the time a machine is working, as described in the following formula:

$$A = \frac{MTBF}{MTTR + MTBF} \quad (6)$$

where A represents the availability, MTBF (Mean Time Between Failure) represents the average time a processing machine works without failure defined as the number of failures divided by the hours under observation and MTTR (Mean Time To Repair) represents the average time to repair a machine, respectively.

In case machines are connected in series as an integrated system based on a R2R method, it will lead to the following consequences:

- The reliability of the total system will dramatically decrease resulting in substantially short MTBF and practically substantially long MTTR of the total system.

- Likewise it will dramatically decrease the availability of the total system. A system with low availability requires high WIP as a 'buffer' in order to provide protection against throughput loss.

- A conventional approach to improve the reliability of the total system consisting of the number of machines is to connect identical machines in parallel per process step. This approach however can hardly be applied on a R2R method.

3. Conclusion

Based on the results of the analysis on manufacturing methods by using manufacturing metrics, we may draw the following conclusion:

- A R2R based system will inherently result in an excessive WIP in a discrete way leading to extremely long cycle time as well as long learning cycle.

- In case a R2R manufacturing method is applied on manufacturing process of flexible microelectronics, which incorporates with many process steps, it can only become attractive when technical breakthrough, which must exclusively be applicable to a R2R but not to a S2S, is made on:
  - Simpler processes
  - Shorter process time ('second' order rather than 'minute')
  - More stability in processes
  - Smarter in-line process control ('on-the-fly')

- An approach to reduce the total WIP in the manufacturing process is to integrate various process steps into one system. This approach however will require the extremely high reliability of each process step; otherwise both the availability and the reliability of the total manufacturing process will be substantially low.

4. Reference

[1] J.D.C. Little, A proof of the queuing formula L=λW, Operation Research **9** (3) (1961)

5. Acknowledgement

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