IV. A SIGNAL-TO-NOISE RATIO VIEW OF INTEGRATED CIRCUIT FABRICATION

A signal-processing view of the processes involved in fabricating an integrated circuit has much to offer in terms of understanding the fundamental limits that apply to this technology. Such a view is suggested naturally by the image-processing steps involved in the photolithography. But a signal-processing view is also useful in describing the various dimensional stability limitations of the materials involved.

PIXEL NOISE

The patterns used to fabricate integrated circuits are all composed of purely black and purely white areas. Such images can be divided by a raster of suitable size into a large number of square picture elements, or "pixels," each of which can be described with one binary bit of information. We therefore think of such a pattern as being a very large number of bits, even though its repetitive nature and its circuit properties make it possible to describe it more compactly in other forms. We will call this the pixel view of pattern replication.

The pixel view is useful for thinking about spot defects in the replication process. Spot defects can be thought of as noise imposed on the information contained in the pixel pattern, just as "snow" on a television picture is noise in the video signal. Given a certain level of noise in a pattern replication process, it is very probable that the circuit involved will fail to work. One could produce a monte carlo simulation that would predict the tolerance of integrated circuits to this kind of noise, provided the circuit dimensions and the statistical properties of the noise were known.

Unfortunately, predicting failure rates on the basis of pattern noise is difficult because the causes of this kind of noise are usually mechanical. Plates get scratched, a mote of dust or a hair mars the pattern, or a crystal defect occurs in the substrate. The statistical properties of these kinds of "noise"--defects that tend to be long and thin--are difficult to describe mathematically, and are quite unrelated to the kinds of Gaussian noise with which information theory is most able to deal. On the other hand, recognizing pattern defects as a kind of raster noise is a useful way to think about the problem.

DIMENSIONAL NOISE

Two kinds of dimensional noise can occur in the pattern replication process. The first is introduced by systematic or random dimensional distortions of the material bearing or receiving a pattern. If one accurately measures the distance between two identifiable points on a silicon substrate as it is passed through various processing steps, a statistical variation in the measured distance will be discerned, even when compensations are made for linear expansion with temperature. These distortions form one kind of dimensional noise, which limits the resolution of the patterns that can be replicated.

A second kind of dimensional noise is introduced by inaccuracies in the alignment of the pattern being replicated. This noise limits the size of the elements that can be reproduced. As the area of the patterns being replicated increases, accurate alignment over the entire pattern area becomes more difficult because of the systematic alignment errors and the distortions in the patterns themselves. Ultimately, both the alignment errors and the pattern distortions limit the number of picture elements that can be reproduced reliably at one step. Because these errors affect the dimensions of various parts of the pattern, we will call this the dimensional view of pattern replication.

The dimensional signal-to-noise ratios required for integrated circuit processing are so high that great care must be taken in the design of equipment to generate and replicate patterns. Two developments worthy of note circumvent the high signal-to-noise ratio requirements by dividing the dimensional accuracy problem into two separate parts. In the EBES system built by Bell Telephone Laboratories, the dimensional accuracy is obtained in part by a moving mechanical stage whose position is measured very accurately by a laser interferometer, and in part by direct deflection of the electron beam. In the fly's eye lens CRT systems, such as those used by General Electric in their BEAMOS memory and by Eiichi Goto (Japan) to generate precision artwork, there is a separation between coarse and fine deflection that permits the burden of the overall precision to be shared by two less-precise processes, or by processes that are precise in different ways.

Similarly, the process of producing whole wafer artwork is commonly divided into two steps: reticle generation followed by step and repeat. Reticle generation is a complex process at modest precision; step and repeat is a simple process at high precision. Again, the self-alignment mechanisms used by some of the newer electron optical generation and replication systems make the overall precision problem more manageable. However, in considering any pattern generation or replication process with an overall precision of one part in 10^5, it is essential to understand clearly how that precision is obtained, for one can be sure that it will always be "with difficulty."

In current, integrated circuit fabrication technology, dimensional signal-to-noise ratios on the order of 100 dB are in regular use. This is a remarkable precision for a mechanical process at any scale, considering the dimensional signal-to-noise ratios for other technologies shown in Table 2.

Table 2

DIMENSIONAL SIGNAL-TO-NOISE RATIOS OF VARIOUS INDUSTRIAL PROCESSES

Process	Accuracy	Signal-to-Noise Ratio
Carpenter	1/8 in. over 10 ft	60 db = 1 in 10^3
Conventional color printing	200 screen over 20 in.	72 db = 1 in 4 × 10^3
Machine shop	0.002 in. over 10 in.	74 db = 1 in 5 × 10^3
Automobile pistons	0.0002 in. over 2 in.	80 db = 1 in 10^4
Surveying manual means	1/10 in. over 100 ft	80 db = 1 in 10^4
Navigation	1 mi over 10,000 mi	80 db = 1 in 10^4
Routine optical components	Fraction wavelength over several centimeters	100 db = 1 in 10^5
Step-and-repeat camera	1 μm over 10 cm	100 db = 1 in 10^5
Integrated circuit fabrication	1 μm over 10 cm	100 dB = 1 in 10^5
Special optical components	1/20 wavelength over many inches	126 dB = 1 in 2 × 10^6
Laser interferometer	0.16 μm over 60 m	126 dB = 1 in 2 × 10^6 (frequency stability limit)
Speed of light measurement	0.33 ppm	130 dB = 1 in 3 × 10^6
Frequency counter HP5345	---	160 dB = 1 in 10^8
Time measurement cesium beam standard	---	220 dB = 1 in 10^{11}