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Semiconductor Manufacturing Technology at IBM

IBM's current semiconductor manufacturing processes are summarized. Briefly outlined are highlights of salient features of semiconductor manufacturing that established IBM leadership and direction for embarking on VLSI production. Some of these features are taken from papers already published; others are from articles in this issue of the IBM Journal of Research and Development ranging from silicon crystal growth through quality control and automated logistics and dispositioning of tested product.

Introduction

The technology of manufacturing semiconductor integrated circuits has developed over the past nineteen years and is still evolving in IBM worldwide, in Burlington, Vermont, East Fishkill, New York, Essonnes, France, and Sindelfingen, Germany. Semiconductor technology has continued to play an important role at IBM as semiconductor components have become an increasingly larger part of the final product. Semiconductor components underpin almost every IBM product from electronic typewriters through large-scale data processors and are a key element in the competitive ability of the company's products.

The semiconductor industry experienced an extremely active period of innovation in the 1970s in the areas of circuit design, chip architecture, design aids, processes, tools, testing, manufacturing architecture, and manufacturing discipline. The combination of these innovations has enabled the industry to enter the VLSI era with the ability to mass-produce chips with 100 000 transistors per chip at the end of a decade after beginning the LSI era in 1970 with only 1000 transistors per chip.

IBM's current basic manufacturing processes produce two major types of semiconductor technologies, the metal-oxide semiconductor field-effect transistor (MOSFET) [1], plus its follow-on called SAMOS (silicon and metal oxide semiconductor) [2], and the bipolar technology [3]. A wide range of logic, memory, and special components are manufactured using these technologies for IBM products.

The introduction of large-scale integration in the mid-seventies identified a number of areas where improvements were necessary for very-large-scale integration. IBM semiconductor manufacturing defined a set of objectives required for the success of future products. These objectives were (1) to provide finished hardware to product designers for engineering changes within fifteen days from receipt of the order, (2) to achieve high yields on LSI and VLSI product parts, and (3) to provide the quality necessary to achieve the demanding system reliability requirements of the product users. A decision was also made to develop further certain technologies which were capable of meeting future requirements, such as the controlled collapse chip connection (C4), which provides multiple interconnection points on a single chip [4], and gate array chips, which have been used in IBM for many years [5].

The objectives were accomplished by providing a quick-turn-around-time facility (QTAT), which can personalize LSI and VLSI chips in less than ten days [6] and with associated electron-beam [7] and tester systems [8] can provide engineering hardware in fifteen days. A comprehensive yield management system was implemented which provides the ability to fabricate highly complex logic chips with yields equivalent to their less complex predecessors in the early 1970s as well as 64K RAM chips with very high test yields. Redundancy schemes involving partially good chips uniquely packaged [9], as well as extra bits designed into memory chips and activated with fuse-blowing techniques, have contributed significantly to achieving good yields early in the life of a product [10]. Improvements in facilities, tooling, and contamination control, with a commitment to superior quality, have resulted in high-density chips which are as reliable as their simple predecessors, in spite of the large number of additional circuits and bits.

The demand for increased performance, density, and reliability combined with lower manufacturing cost of semiconductor integrated circuits has given rise to significant developments in virtually all fields of semiconductor processing. Contained in this issue are ten selected articles which describe the ongoing developments in the fields of silicon processing, lithography, quality and yield management, measurement, control, and testing which are part of our state-of-the-art semiconductor manufacturing processes.

Silicon processes

The silicon wafer is the prime starting material for semiconductor fabrication. Knowledge of this material is expanding as the demand for improved quality requires the growth of more perfect silicon crystals [11]. As silicon wafers are processed through the semiconductor line, they must remain defect-free in the area of the device structure but be capable of gettering impurities by internal defect generation away from the device structure or by external means on the back side of the wafer. Ion implantation [12] has been incorporated into IBM's semiconductor production facilities. In addition to low-temperature processing, it offers the advantages of precise control of the total quantity of impurities transferred to the wafer, a high degree of uniformity across the wafer, and accurate control of depth distribution.

Lithography

The demand for increased circuit density has resulted in significant advances in the field of lithography to the point where micron and sub-micron dimensions are being considered for future products [13]. With the capability of producing small horizontal dimensions with optical means approaching 2 μm, it is equally important to be able to control the tolerances of these dimensions which have been correlated to phenomena in the photoresist systems used [14]. A key ingredient of optical lithography is the photomask, where a lot of activity revolves around the discovery of new and better materials which manufacturing engineers are eager to exploit. But improvements here must go hand in hand with the need to develop improved metrology [15].

Mask-making, using electron beams rather than optical light sources, and the use of IBM-developed tools have paved the way for finer lines and spaces. In conjunction with that development is the need for achieving reduced horizontal dimensions in metal interconnecting films through the use of lift-off technology [16]. This technology has the advantage of smaller achievable dimensions to define patterns on metals which are otherwise difficult to etch, on composite metals, or on underlay materials which may be attacked by chemical etchants.

With dimensions of less than 2 μm, alternate lithography means are being pursued. Direct wafer-write electron-beam systems have been in use at IBM for several years [17] and offer the advantage of excellent resolution and overlay, reduced defects, and quick turn-around time due to the elimination of the mask. Electron-beam proximity printing is being pursued as an alternative which would reduce the cost compared to direct-write systems [18].

Measurement, quality, yield, and control

The need for increased densities and reduced cost has put significant demands on measurement and control systems. These systems can be literally microscopic (to measure small images) or macroscopic (to control process commonality between manufacturing sites worldwide). Other examples of measurement and control include pulsed-bias CV techniques to measure implanted dopant profiles and uniformity [19], and adaptive control systems [20] allowing the use of flexible controllers which can continuously adapt to process changes. Computers are not only used extensively to control tools but also to track the key parameters of all critical processes [21].

A completed LSI chip is formed only after being processed through hundreds of complex operations, such as plasma processing [22], which can take many weeks. It is critical that an effective quality management system [23] and yield management system [24] be in place, not only to measure quality and project yields while monitoring both continually, but also to provide quick feedback to keep the process in control, thereby minimizing yield losses and reprocessing steps. These systems, along with in-depth characterization and failure analysis, provide a unique ability to manufacture complex products with the required yields.

IBM's commitment to open part number sets drives a requirement for quick turn-around time. Open part number sets, by their nature, are prone to engineering changes as a system is being optimized. This quick turn-around-time capability is required for new parts to minimize the time needed to debug a hardware system. It is met by an automated computer-controlled line [25] which is capable of personalizing custom parts in less than ten days.

To implement an open part number set requires comprehensive design and logistics systems which permit a circuit designer to customize components at a remote site and expect to receive hardware which performs to desired specifications. The specifications are ensured by a test system which verifies that the product meets the requirements [26]. A final logistics system provides for automatic product dispositioning and verifies part number yields [27].

Summary

IBM's published articles on semiconductor manufacturing indicate its commitment to continued excellence in its products. A fundamental technical understanding of today's processes and tools is essential for success. This pursuit has resulted in high-quality standards coupled with high yields on existing products, thereby reducing their costs substantially. It is expected that the ongoing work reported here and elsewhere will provide the basis for maintaining IBM's leadership role in the development of the next generation of semiconductor products, and that this next generation will in turn provide enhancements and new direction for future IBM products.

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