technology possessing the advantages of higher packing density per slice and considerably lower power dissipation.[66] Since fewer process stages were needed, yields were higher and manufacturing costs correspondingly less. A major cause of failure with discrete devices is due to faulty intermetallic connections. Since, in the case of integrated circuitry, electrical connections could be made from one device to the other by aluminum deposition onto the surface of the slice, using photomasking and etching techniques, the need for intermetallic connections was confined to attaching the chip to its external electrical contacts, thus greatly improving reliability. The combination of these two factors—increased reliability with decreased cost, achievable through the use of MOS technology—are the major reasons for the success of the integrated circuit in its present form.

Two basic types of MOS circuit have been fabricated, P–MOS and N–MOS. P–MOS devices are manufactured with an N-substrate and P-type source and drain diffusions. N–MOS devices are manufactured with a P-type substrate and N-type source and drain diffusions. Electron mobility in silicon is about twice that of hole mobility, consequently the N-MOS FET (in which the majority carriers flowing in the channel are electrons) is a higher speed device than its P–MOS counterpart. In addition to its higher speed, the N–MOS FET has the advantage of a higher packing density (a higher number of devices per unit area). However, the N–MOS devices are more difficult to manufacture, owing to the electric charges present at the oxide–silicon interface (often due to contamination) which are positive in polarity and tend to turn on the device. Consequently, most of the earlier devices produced were of the P–MOS type. These difficulties have since been satisfactorily solved and N–MOS has now become the preferred logic for large-scale memories.

An important improvement which took place during the mid-1970s was the development of silicon-gate MOS, which further simplified the fabrication process, allowing smaller devices to be made, with speeds that are now approaching that of bipolar logic. The 'complementary' MOS configuration (CMOS) developed by Wanlass and Sah in 1963 uses both N–MOS and P–MOS devices.[67] This approach has the advantage that power is only taken from the supply during the period when the device actually switches states. Consequently, CMOS has been widely used in such fields as hand held calculators, portable equipment and aerospace systems, in which battery drain is an important factor.

4.11 Genesis of the monolithic integrated circuit

The concept of the monolithic integrated circuit (IC) appears to have first been made public by G.W.A. Dummer of the Royal Radar Establishment (RRE) Laboratories, Malvern (UK). Referring to this event, Roberts writes:

> 'It is widely acknowledged that the first public reference to the possibility of achieving a complete circuit function in a single solid block was made by G.W.A. Dummer at a conference in Washington DC in 1952.'[68]

Roberts states in the same article that:

> 'I believe that the idea had emerged in discussion between Dummer and members of Caswell Research Laboratory of the Plessey Company Ltd.—specifically G.C. Gout (Director of Research) and N.C. Moore (Research Manager).'

From the outset therefore, a link in this field between a government research establishment and industry was established.

Also, at about this time, the idea that it might be possible to fabricate an integrated circuit had been put forward in the United States and the first patent for such a device was filed on 21st May 1953 by H. Johnson of the Radio Corporation of America (RCA), this being for a 'semiconductor phase shift oscillator and device'.[69] The proposed circuit consisted of a transistor and a resistance–capacitance phase-shift network, the capacitors being reverse-biased P–N junctions. However, it appears that no significant development followed from this proposal.

In the mid-1950s on the initiative of Dummer, a tentative beginning was made in Britain, although according to Atherton:

> 'Plessey appeared to have regarded the idea as "a laboratory curiosity, or at best as an exploratory feasibility study".'[70]

Kilby states that:

> 'In 1956, Dummer let a small contract to a British manufacturer (The Plessey Company Ltd). They were unsuccessful in realising a working device primarily because they were working with grown junction transistors.'[71]

However, an appreciation of silicon as a suitable material for the construction of integrated circuits was realised at the time. Golding writes that:

> 'as early as 1956, researchers in the Physics Group at RRE began to realise that a silicon crystal exhibited all the electrical properties required for the construction of a complete circuit function, an observation which predated the similar in sight of J.S. Kilby at Texas Instruments by some eighteen months.'[72]

As a result of the work carried out at RRE, Dummer mentions that

> 'a contract was placed with the Plessey Company Research Laboratories in April 1957 for the development of Semiconductor Integrated circuits'[73]

and a model (made of card and paper) was exhibited of an IC flip-flop circuit at the International Components Symposium at RRE in September 1957, this event stimulating considerable American interest. However, according to Roberts, at about this time:

> 'possible action at Caswell on the true silicon solid-state circuit was delayed by the departure of J.T. Kendall to join Texas Instruments, breaking the continuity of speculation on solid circuits.'[74]

The Plessey team then comprised only five qualified personnel, but were already using advanced techniques, such as diffusion in silicon and etching processes similar to those used later by Kilby. However, in spite of this early start, the integrated circuit concept did not appear to have made any appreciable impact, and when no government funds were forthcoming, the idea was abandoned.[75]

Therefore, during the period when American interest in this field was rapidly growing, little work was being done in the UK despite a promising start, and the early technical lead was lost. Dummer writes that:

> 'Although early work had been done in the field of IC's by Plessey and RRE's Physical Lab., it was not until February 1960 that a team was formed at RRE to study semiconductor techniques.'[76]

At this stage it was felt necessary to obtain Government support in order to stimulate development in the integrated circuit field; consequently a working party was set up by the Admiralty, under the co-ordination of the valve development organisation (CVD) which covered contracts on active (amplifying) devices. The result was that contracts were then placed with a number of companies including Texas Instruments Ltd. (Bedford), The Plessey Company Ltd., Standard Telephones and Cables Ltd., and the Ferranti Company Ltd. The rather leisurely tempo with which developments had proceeded in Britain contrasted with the work carried out in the United States, principally by the Fairchild Corporation and Texas Instruments Ltd (Dallas), the latter firm instituting a six months crash programme in the beginning of 1961, which resulted in the market introduction of a range of planar integrated circuits in August of that year. This programme was instituted following the development of the integrated circuit concept in 1958 by J.S. Kilby, then working for that company.[77] By the summer of the same year he had fabricated the first operational semiconductor circuit, a simple phase-shift oscillator, although using germanium rather than silicon for its construction. He later produced the first working model of a silicon integrated circuit (a simple multivibrator) which was completed on 28th August 1958, this device using silicon pre-etched grown junction transistors. The concept was announced publicly at a press conference in New York on 6th March 1959, and was widely reported in the press.[78] As a result of Kilby's work, the US Air Force issued a contract for further investigation. Within one month from that date Kurt Lehovic of Sprague Company had filed a patent application (22nd April 1959) for the use of reverse-biased P–N junctions to perform the function of isolation diffusion, thus enabling individual components on the chip to be electrically isolated from each other.

The most significant advance was, however, made by R. Noyce of the Fairchild Corporation, who, six months after Kilby's success, produced the first silicon planar integrated circuit, thereby rendering the concept commercially viable.[79] By March 1961, ahead of Texas Instruments, Fairchild produced the first market range of integrated circuits. This method allowed the simultaneous fabrication of transistors, diodes, resistors and capacitors on a single silicon chip. The earliest monolithic integrated circuits were based on 'mesa' technology, and because of the limitations of that technology were inferior to contemporary discrete devices. However, the newly invented planar process was instrumental in providing the desired breakthrough, allowing rapid microminiaturisation to proceed. Improvements in photolithographic techniques quickly reduced the size of the components and enabled multiple circuits to be constructed on a single chip. The rapidity of this development is evident from the following statement made by Brothers:

> 'The complexity of integrated circuits has grown from three transistors and one resistor in 1960 through some 40 odd components in 1964 to some 12 000 components in 1972.'[80]

and in this context Shepherd writes:

> 'thus, in the 1960s bipolar digital circuits progressed from a chip containing a single logical gate to a chip on which a complete small computer central processor can be made.'[81]

This swift and successful development in the United States came about directly as a result of military involvement. Bridges quotes the (US) Director of Defense Research on Engineering stating in a memorandum to the military departments in April 1963: 'This gain in reliability, coupled with reduction in size, weight and power requirements and probable cost savings, make it imperative that we encourage the earliest practicable application of microelectronics to military electronic equipments and systems'.[82] Certainly by the mid 1950s a need had arisen in military circles for a solution to the problem of conflicting demands of increasing complexity versus reliability. In the case of missile systems, the factors of size, weight and power consumption were also vitally important. A further factor was the reduction in maintenance—indeed, in space and missile systems this procedure could hardly be carried out once the system was in operation. The same problems which had presented themselves in connection with thermionic valves towards the latter end of the 1940s, and for which discrete transistors presented a solution, now arose again at a more advanced technical level.

External political factors may also have played a part in the decision of the United States Government to offer substantial assistance to the semiconductor industry at this time. Braun and MacDonald write:

> 'some observers see it as no coincidence that heavy military funding should have commenced so soon after the launching of Sputnik in 1957.'[83]

In that year, a microcircuit programme was started at the Diamond Ordinance Fuze Laboratories, involving printed circuit techniques. (This was a military research organisation which maintained close links with Bell Laboratories.) Important advances were made there at this time in photoresist techniques, and the step and repeat camera, used to design photomasks, was also invented there. These developments were soon to play a vital role in the technology of the planar process.

Several approaches to the problem of circuit integration were attempted; for example, the 'micromodule' supported by the US Army, based on the earlier 'Tinkertoy' concept of discrete devices stacked in a three-dimensional array. Also in the same year (1958) the US Navy sponsored the thin-film approach. Although it was technically feasible to manufacture passive components by this

> 'we are sure now that our action in the spring of 1959 was right, that it did advance the availability of usable integrated electronic devices by at least a year, possibly two. In the five years since then, the Department of Defense has spent around thirty million dollars in support of R & D and work on manufacturing methods in integrated electronics. Of much greater significance, however, has been the rapid increase in integrated electronics R & D and production facility support sponsored by industry. It is hard to estimate the amount accurately, but it has certainly been several times the size of the government's effort—perhaps ten times as much'.[85]

The money invested by industry was, however, spent with the knowledge that a substantial military market existed which would absorb the product (in the event of it being successful) at least during the critical initial phase when production yields were low and manufacturing costs high. As can be seen from Table 4.4, initial supplies of integrated circuits were almost entirely to the military during the early years of production. Therefore, as in the case of the discrete transistor, the US Government acted to 'prime the pump' not only financially but by assisting research, development (R & D) and production engineering, but, more importantly, by providing a guaranteed market for the product.

The first commercial application for the integrated circuit in 1963 was in the hearing-aid market,[86] suggesting that the same considerations which determined the original use of the transistor rather than the thermionic valve in this application again applied—for example, a decrease in size and weight and also lower power consumption than its predecessor, the latter factor leading to a decrease in battery costs would tend to compensate for the higher price of the integrated circuit.

Table 4.4 Average uncorrected price of IC's and proportion of production consumed by the military

Date	Average price ($)	% Consumed by military
1962	50·00	100
1963	31·60	94
1964	18·50	85
1965	8·33	72
1966	5·05	53
1967	3·33	43
1968	2·33	37

Source: Tilton J., 'International Diffusion of Technology', 1974 p. 91; and 'EIA Market Data Book', 1975 p. 86

Table 4.3 US sales of transistors at beginning of 1960s

Year	Germanium Units	Average Value	Silicon Units	Average Value
	$\times 10^6$	$	$\times 10^6$	$
1957	27·7	1·85	1·0	17·81
1960	119·1	1·70	8·8	11·27
1963	249·4	0·69	50·6	2·65

Source: EIA Market Data Book, Washington DC, 1974

method, active devices (i.e. transistors) could not be fabricated successfully. A further approach was that of the US Air Force which supported the Westinghouse company in developing what was termed the modular electronics concept, the aim being to construct monolithic units capable of performing a given function without themselves containing discrete elements.

In view of this activity, it certainly appears that at this time the military authorities were urgently working for a solution to the problems arising from the growing complexity of electronic systems and were prepared to fund any approach which seemed to have some chance of success. This climate of opinion could hardly fail to act as a stimulus to those who were attempting to construct integrated circuits, particularly since, should their attempts be successful, the opportunity to supply the highly lucrative military market existed. The intense and rapidly successful efforts at integrated circuit production both by Fairchild and Texas Instruments should be seen in this context.

A further factor acting to encourage semiconductor manufacturers of this time to explore alternatives to discrete devices was that, by the beginning of the 1960s, semiconductor prices had fallen sharply as volume production increased. For example, the US sales of germanium and silicon transistors were as in Table 4.3:

The prospect of declining profits as the market became saturated with discrete transistors cannot be discounted as an additional spur to efforts made by transistor manufacturers, particularly those who specialised in semiconductor fabrication to the exclusion of other activities. In this context, Braun and Macdonald write:

> 'The integrated circuit was, among other things, a solution to the commercial bottleneck problem—too many companies producing too many discrete components at too low prices.'[84]

It would appear, therefore, that an urgent need existed for both the US military authorities and the semiconductor manufacturers to develop the new product, and this was demonstrated by the willingness with which Government and Industry invested considerable sums of money in order to do so. The US Government Deputy Director for Electronics (Department of Defence), J.M. Bridges, writes in December 1964: