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HISTORICAL OVERVIEW OF SILICON CRYSTAL PULLING DEVELOPMENT

Werner Zulehner*

Wacker Siltronic AG, Postfach 1140, D-84487 Burghausen, Germany

Abstract

The first silicon single crystals were grown by crucible pulling in 1950, two years after the invention of the transistor which was first made from germanium. Two years later, the crucible-free float zone pulling was invented. In this stage, the low purity of the starting polysilicon for the crystal pulling was the biggest problem. A great help in the purification of polysilicon were the very low distribution coefficients of most of the impurities. This effect was used in the refining of silicon by repeated crucible-free zone melting (zone refining). However, boron cannot not be sufficiently removed by this technique. Since 1961, the raw silicon is first transformed into a silane, then the silane is purified by distillation and adsorption and finally retransformed to elemental silicon by chemical vapor deposition. This purification technique yields a polysilicon which needs no further purification by zone refining. A big step forward was the invention of the dislocation-free crystal growth in 1958, an absolute necessity for the manufacturing of highly integrated devices. The first crystals were small with about ½ inch diameter and about 100 g weight. Predominantly for economical reasons, the size of the crucible pulled crystals increased about every four years stepwise to 12 inch in diameter (for 300mm-wafers) and to 250 kg in weight till today. The maximum diameter of float-zone grown crystals is only 6 inch at present, because there was no need for larger FZ-Si diameters in the past. But this has changed recently.

Keywords

Historical overview, silicon crystal pulling, Czochralski, float-zone, poly silicon.

*Author: Tel: +49-8677-832547, Fax: +49-8677-837303, E-mail: werner.zulehner@wacker.de

Introduction

At present, about 99 % of all semiconductor devices are made from monocrystalline silicon. Considering the enormous importance of electronics in the current technology, industry, and life, this means, that single crystal silicon is one of the most important technical materials today and in the nearer future. Most of today's apparatuses or machines do not work without electronics. In 1998, semiconductor silicon for about 7 billions US $ was produced. From this material, semiconductor devices for about 140 billions US $ and electronic units for about 1800 billions US $ were manufactured.

Most of the electronic devices must be made from dislocation-free monocrystalline silicon of high crystalline perfection and homogeneity. Only some simple devices can be made from dislocated or coarse grained polycrystalline silicon. In all cases, however, the functioning and the manufacturing yield of the devices is better if highly perfect silicon single crystals are used. The degree of crystalline perfection and purity increases with increasing package density at the highly integrated low power devices and with increasing voltage and current in the case of high power devices.

In the beginning of silicon single crystal growth, the researchers had to struggle mainly against the impurity of the material. The subsequent development steps were: elimination of the dislocations; reduction or elimination, respectively, of the swirl-like microdefects (small extrinsic dislocation loops); reduction in number and size of the voids (agglomerates of vacancies); reduction and homogenization of the oxygen content in crucible pulled crystals. The purity of the crystals was improved permanently. Mostly by economic reasons, the diameter of the crystals was increased step by step from ½ inch to 12 inch up to now. At present, about 95 % of all silicon single crystals are grown according to the Czochralski (CZ) technique and rest by the float-zone (FZ) technique. CZ-Si is predominantly used for the manufacturing of highly integrated low power devices and FZ-Si is predominantly used for high power devices.

Historical development

History of Silicon

The word silicon is deduced from the Latin "silex" for flint stone which is mostly amorphous SiO_2. Silicon was first produced as a mixture of silicon and iron in the year 1810 by Berzelius. In 1823 he obtained iron-lean silicon by reducing SiF_4 with potassium metal. Commercial production of silicon started in 1902 in the form of ferrosilicon, an iron-silicon alloy with typically 25 % by weight iron, which was used in the steel industry as an excellent deoxidant for steel melts. The purer metallurgical grade silicon came up in industrial production, when it was needed as an alloying element for aluminium. Ferrosilicon and metallurgical grade silicon are nearly exclusively produced by carbothermal reduction of quartz and quartzite. At present, more than 1 million tons metallurgical grade silicon containing typically 99 % silicon are produced per year. Ca. 60 % of it are used in metallurgy, ca. 35 % for the production of silicones, and ca. 5 % for the production of semiconductor silicon. The main impurities of metallurgical silicon are Fe, Al, Mg, and Ca. For semiconductor applications, the metallurgical grade silicon is much to impure. The total concentration of elements other than carbon and oxygen must be reduced to below 1 ppba. Only the electrically inactive elements carbon and oxygen, and for special purposes also nitrogen, are each

allowed to occur in concentrations above 1 ppba. The chemical vapor deposition of silicon on hot surfaces using chlorosilanes and hydrogen was already invented in 1890 by Langhans, [1], for the protective covering of incandescent filaments long time before semiconductor silicon was produced.

Chemical refining of silicon

In the time before silicon was used for semiconductor applications, the usual production process for a silicon purer than metallurgical grade silicon used the chemical vapor deposition reaction

$$(SiCl_4) + 2\,(Zn) = <Si> + 2\,(ZnCl_2). \qquad (1)$$

The drawback of this process was that the $SiCl_4$ always contained BCl_3 which was reduced by Zn in the same way to elemental boron, i.e. the deposited silicon was always contaminated with boron. Therefore, in 1943, G.K. Teal and K. Storks, who made polycrystalline silicon microwave diodes by chemical vapor deposition, replaced tin in reaction (1) by hydrogen, [2]:

$$(SiCl_4) + 2\,(H_2) = <Si> + 4\,(HCl). \qquad (2)$$

Hydrogen is not able to reduce BCl_3, therefore, boron remains in the gas phase, so silicon contains much less boron. Short time later, they replaced silicontetrachloride $SiCl_4$ by trichlorosilane $SiHCl_3$ which could be easier reduced or dissociated, respectively.

Czochralski crystal growth

In the year 1916, Jan Czochralski, a polish metallurgist, working in Berlin, cofounder of the German Metallurgical Society, published a method for measuring the maximum crystallization rates of metals, [3]. He pulled metal wires of ca. 0.8 mm in diameter vertically from melts with increasing velocity until they tore off from the melt. In his experiments, single crystalline wires occurred and he recognized that with this pulling technique, single crystals could be grown successfully if single crystal seeds are used.

After the invention of the point-contact transistor in the Bell Laboratories in Dec. 1947 by John Bardeen and Walter H. Brattain [4], and of the junction transistor by William Shockley [5] on the basis of germanium, first germanium single crystals were grown in 1948 according to the CZ method by G.K. Teal and J.B. Little, [6, 7]. At the end of 1949, Ernie Buehler joined the crystal growth activities, and the crystal puller and the pulling process were improved step by step and patented, [8, 9]. During the first half of 1950, a more sophisticated crystal puller was designed and built, in which the graphite crucible with the melt was inside a quartz glass tube and the heating induction coil immediately outside of the glass tube. This improved the cleanness of operation. The seed was attached to a rotatable and vertically movable spindl. Fig. 1 shows their improved growth apparatus which was equipped with devices for double doping of the crystal for the generation of p-n or n-p-n junctions in the crystals. With the help of this crystal puller, the first n-p-n transistor of Shockley was produced.

In 1949, W.J. Pietenpol and R.S. Ohl built the first transistor made from silicon [10]. Soon, one recognized that silicon was the better semiconductor material for most of the devices, and in 1951, Teal and Buehler, [11], started to grow also CZ-Si crystals, using a polycrystalline silicon which was produced according to the method of J.H. Scaff, H.C. Theuerer, [12]. For the growth of silicon crystals, quartz glass crucibles must be used, which because of their softness at high temperatures,

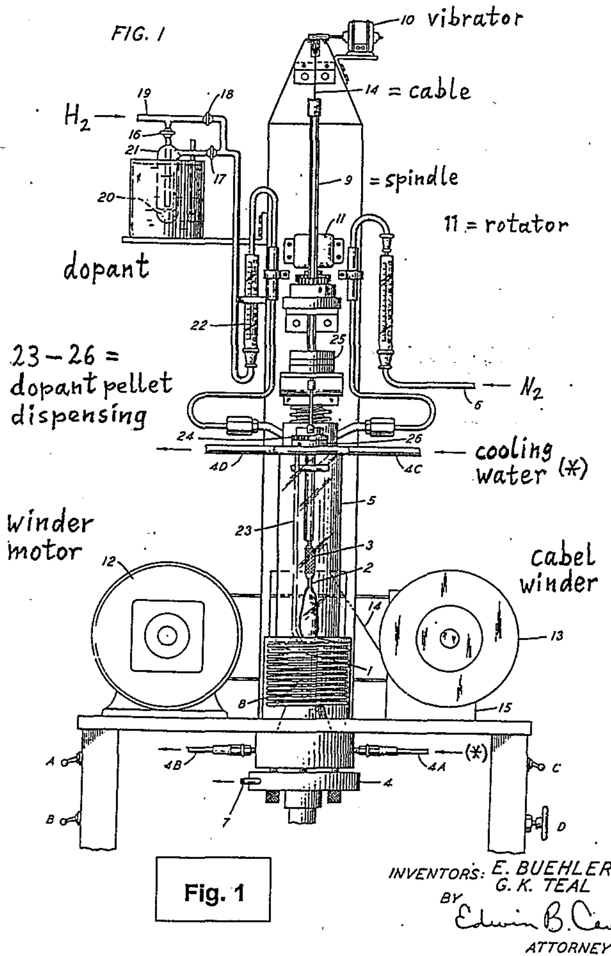


Fig.1. CZ-Ge single crystal growth apparatus for double doping of E. Buehler and G.K. Teal from the year 1951; patent drawing.

must be supported by graphite crucibles. The crystal puller had to be purged strongly with a noble gas (argon or helium) to remove quickly the large quantities of silicon monoxide which evaporated permanently from the silicon melt. Without purging, soon a slag of SiO, SiO_2, and Si would form on the melt surface and the growth of a single crystal would be impossible. The weight of their melts were between 50 and 100 grams and the diameters of the crystals around ½ inch. With single crystal seeds, they could grow dislocated single crystals of specified orientations. Dislocation-free crystal growth was invented some years later.

Segregation, special case oxygen

In the first years, the biggest problem was to produce a silicon which was pure and crystalline perfect enough for the manufacturing of good semiconductor devices. At the problem of refining silicon, nature was just as helpful as in several other process steps necessary for realizing silicon semiconductor electronics. Solid silicon shows a very low solubility for most of the elements, much lower than liquid silicon, resulting in a strong segregation of these elements at freezing. A typical example is iron which shows a distribution coefficient of 6.4×10^{-6}. This distribution coefficient means that from 150,000 iron atoms in the melt at the freezing interface only one iron atom is incorporated into the growing crystal. Nearly all iron atoms remain in the melt. Therefore, the crystallization of silicon is a strong refining step for most of the elements. The result of refining is the better the larger the melt is. Usual CZ growth has the largest possible melt because all material is liquid and consequently shows the strongest refining effect per freezing. The segregation of the impurities at CZ growth is described by the law of "Normal Freezing":

$$C_X = k * C_O * (1-x)^{k-1}, \quad (3)$$

with k = effective distribution coefficient, $x = m/m_O$, m_O = mass of the starting melt, m = crystallized mass, C_O = concentration in the starting melt, C_X = concentration in the crystal at the freezing interface. Fig. 2 shows the axial impurity distribution in CZ-Si and in modern FZ-Si crystals for some impurity elements. The refining effect per freezing is much smaller at FZ growth because the FZ melt is much smaller than the CZ melt. This is in particular true for the constricted FZ-Si melts which must be applied at the growth of large diameter crystals. With the old ½"∅ FZ-Si crystals, the melts amounted typically to 5 to 10 % of the total crystal mass, compared to

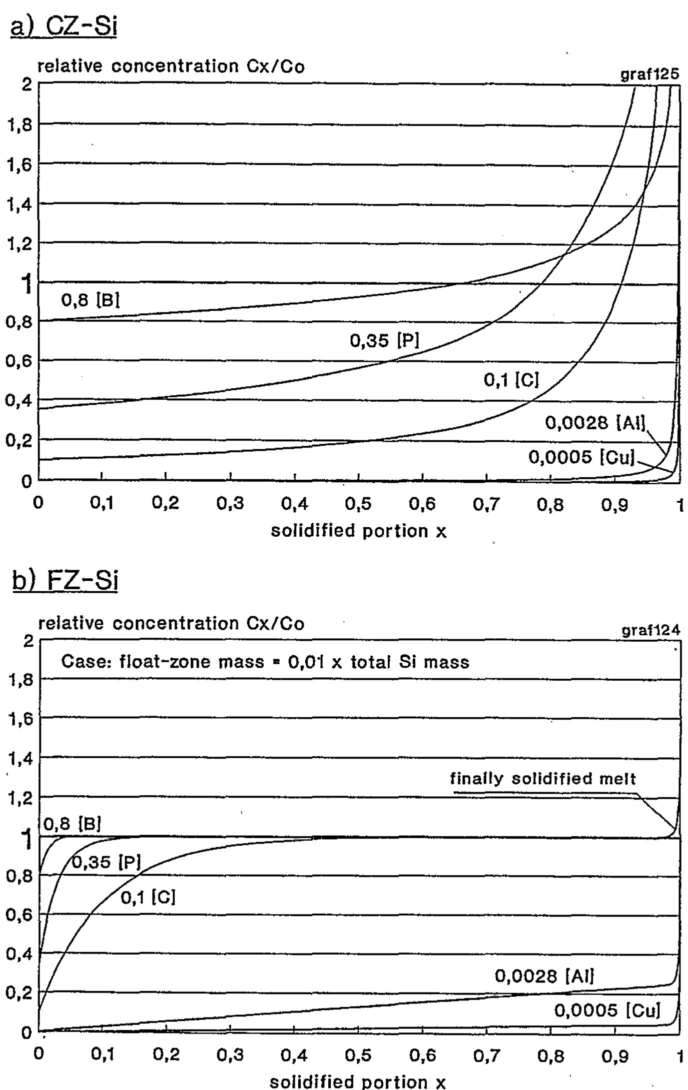


Fig. 2. Axial impurity distribution in CZ-Si and FZ-Si for the case that the impurities are homogeneously distributet in the starting material.

melts of only 1 to 2 % at modern 4"∅ FZ-Si crystals. The percentage of the FZ melt depends inversely proportional on the length of the crystal.

The refining effect at CZ-Si growth is reduced to some extent by the effect that silicon reacts with every crucible material to a more or less large extent what introduces impurities from the crucible material into the silicon melt. Fortunately, there is one crucible material, i.e. silica, of which the silicon does not disturb and oxygen evaporates easily from the melt in the form of silicon monoxide SiO. The strong evaporation of SiO prevents the supersaturation of the melt with oxygen. Supersaturation of any impurity must be prevented because it leads to dislocated and finally to polycrystalline growth. Normally, more than 99 % of the oxygen introduced into the melt by silica dissolution evaporate at the free melt surface. These two conditions are not given with any other crucible material. Silicon carbide and silicon nitride, for example, form no volatile compounds with Si and remain in the melt resulting soon in supersaturation of carbon or nitrogen, respectively. The melt-crucible reaction also introduces the impurities of the dissolved silica into the melt. Today, the total impurity content of quartz glass made from natural quartz is about 10 ppmw, but this is not sufficient. Therefore, synthetic silica is used more and more for the manufacturing of CZ-Si crucibles. The impurity contents of the recent best synthetic silica is < 1 ppbw.

Crucible-free zone refining, float-zone single crystal growth

Since 1951, W.G. Pfann developed and investigated the zone refining of germanium in a strongly elongated boat crucible made from graphite or silica glass, [13, 14]. The boat was first filled with granulated germanium. By passing a short melt zone from one end of the crucible to the other, a big part of the impurities of the germanium were driven by segregation to the end where the melt froze finally. This could repeated several times and the germanium got purer and purer. With zone refining, most of the unwanted impurities can be reduced strongly, but not all. Boron in silicon, for

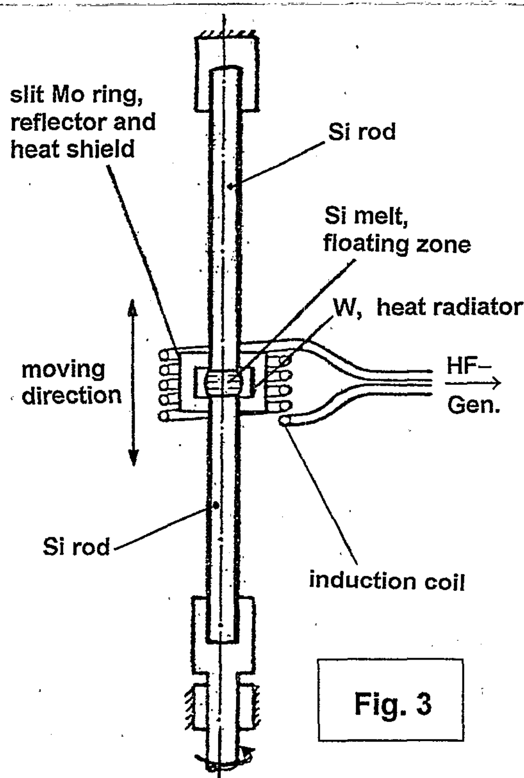
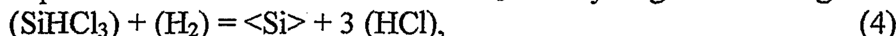


Fig. 3. FZ melting according to R. Emeis for the zone refining and single crystal growth of silicon from the year 1953.

example, cannot be reduced sufficiently. The zone refining works only for impurities with small distribution coefficients. For very low boron concentrations in silicon, other methods like distillation of silanes must be applied. With placing a seed crystal at the starting end of the boat, also the growth of germanium single crystal is possible, but not of silicon single crystals. Liquid silicon reacts too strong with the crucible material and gets polycrystalline.

To apply zone refining also to silicon, several researchers simultaneously started in 1952 to develop or to invent, respectively, the crucible-free zone refining of silicon and, later on, the crucible-free pulling of silicon single crystals: a) P.H. Keck and M.J.E. Golay (Bell Labs.), [15]; b) H.C. Theuerer (Bell Labs.), [16]; c) K. Sieberts and H. Henker (Siemens), [17]; and d) R. Emeis (Siemens), [18]. Fig. 3 shows the float-zone growth arrangement of Emeis, which is very similar to that of Theuerer. With these arrangements, both float-zone refining and float-zone single crystal growth could be realized. Because they first did not use seed crystals, the orientations of the grown crystals were accidental. However, most of the single crystals showed <111> orientation, because this is the most stable and slowest growing interface. The main difference between the growth technique of Theuerer and Emeis was the heating technique. Theuerer used a lateral resistivity heater made of graphite which heated the silicon by heat radiation. Emeis also used heat radiation for melting, but his heat radiator was a circular tungsten sheet which was heated from outside by an induction coil.

For float-zone growth, it was necessary to have the starting silicon in the form of a stable rod which should have about the same diameter as the crystal to be grown. At the Bell Labs., 320 g ingots of 1 ¾ inch diameter and 5 inch length of already rather pure, polycrystalline silicon, grown according to the technique of J.H. Scaff, H.C. Theuerer, and E.E. Schumacher, [19], were taken and machined to small rods of ¼ inch diameter. These small rods were used at first by H.C. Theuerer in his float-zone refining and single crystal growth apparatus described in his patent, [16]. At about the same time at Siemens, G. Ziegler developed the sintering of rods from silicon powder, which was produced by chemical vapor deposition from trichlorosilane $SiHCl_3$ and hydrogen according to the reaction



$$(SiHCl_3) + (H_2) = \langle Si \rangle + 3\,(HCl), \qquad (4)$$

for the float-zone refining and single crystal growth experiments of Emeis, [18].

Chemical vapor deposition of highly pure polycrystalline silicon rods

Siemens favored the float-zone technique for the growth of silicon single crystals because they can be produced to higher purity and with axial constant concentrations of the dopants boron or phos-

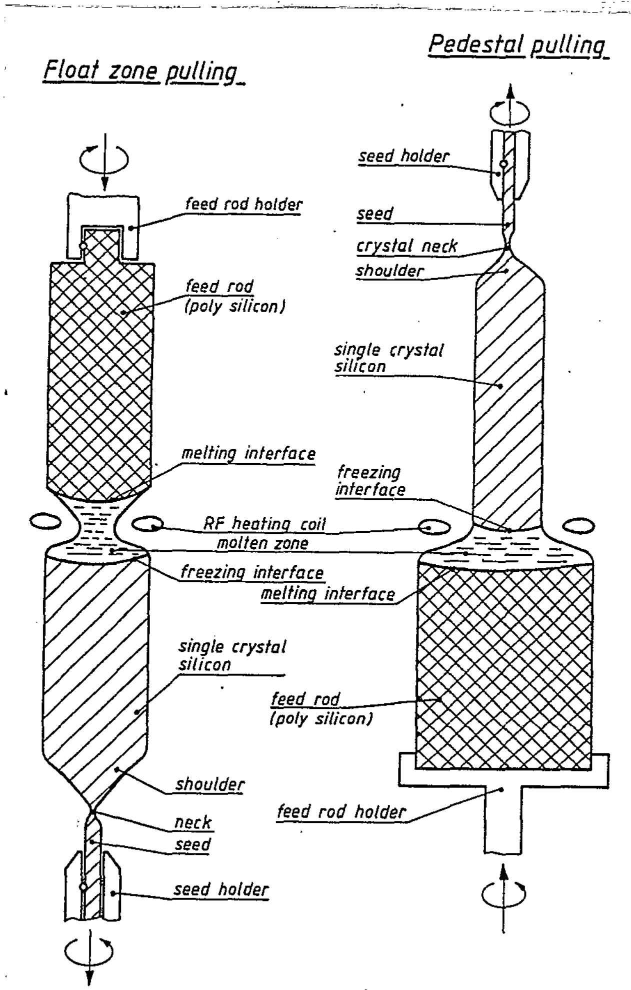


Fig. 4. Schematics of float-zone pulling and pedestal pulling. At pedestal pulling, the crystal is pulled vertically through the induction coil.

phorus, see Fig. 2. This growth technique needs rods of silicon as starting material. Consequently, the people of Siemens decided to produce high purity silicon rods by chemical vapor deposition CVD. In 1953, they began to deposit silicon on hot silicon slim rods, heated to about 1100°C by electrical current. The silicon slim rods were produced by a special float-zone technique, the pedestal pulling technique, Fig. 4. This deposition technique was called "Siemens process". The principle of the Siemens process is shown in Fig. 5 and described in the patents [20, 21, 22]. In this time, the polycrystalline CVD silicon rods were additionally purified by multiple zone refining.

Dislocation-free crystal growth - Dash seeding

With the first seeding technique, a seed crystal of 6 or more millimeter diameter was contacted with the melt and again withdrawn from the melt by keeping the diameter of the seed crystal. After a short growth length, the diameter of the growing crystal was enlarged to the desired crystal diameter. In this case, the dislocations of the seed propagated in growth direction by growing and slipping. The slipping or moving, respectively, of the dislocations is caused by cooling strains in the growing crystal. If dislocations are moving, they often make cross-slip by changing the slip plane, and with that, the dislocations are able to follow the growth interface even they are lying oblique to the growth direction. Dislocations lying oblique to the growth direction grow out to the lateral crystal surface and are left behind by the growth interface if they do not move. In the latter case, the growing crystal gets dislocation-free.

This case is realized by the seeding technique of W.C. Dash, which he developed in 1958, [23]: After connecting the seed crystal with the melt and starting the growth, he first reduced the crystal diameter to about 3 mm and kept it constant for several centimeters and, additionally, increased the growth rate to about 6 mm/min at the same time. Owing to the small crystal diameter, the cooling strains got too low for driving the dislocations behind the fast propagating growth interface. After about 3 cm length, the thin crystal was dislocation-free and the crystal diameter could be enlarged to the desired value. The zone of smallest crystal diameter is called seed neck or crystal neck. Once dislocation-free, the crystal remains dislocation-free also if higher cooling strains occur. A rather high strain is needed to form a first new dislocation in a dislocation-free silicon crystal. But if one first dislocation is formed, then this dislocation is moved by the cooling strains and multiplies

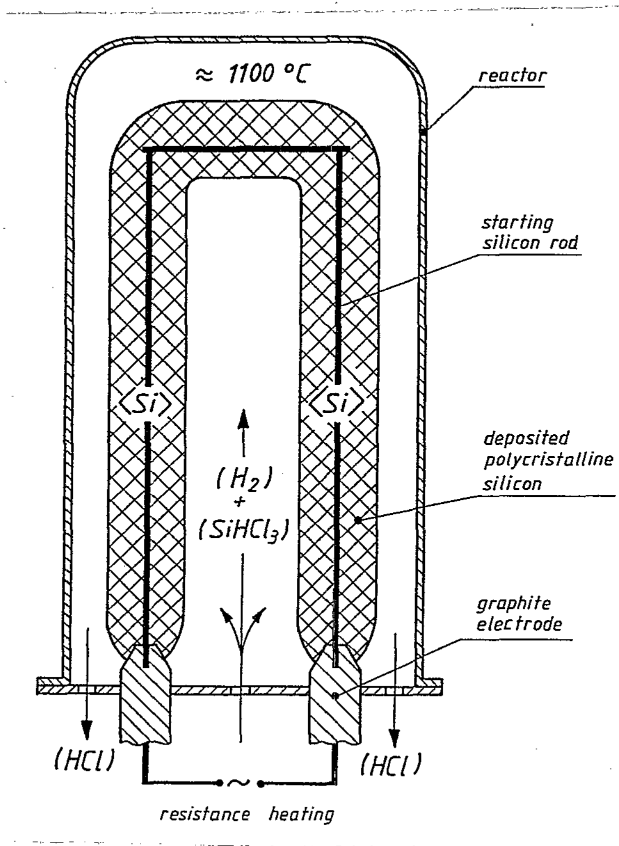


Fig. 5. Chemical vapor deposition CVD of silicon from trichlorosilane and hydrogen on hot silicon slim rods (Siemens process).

extremely fast. This fact results in the large difference between the upper and the lower yield strength of highly pure silicon single crystals. The invention of the dislocation-free silicon crystal growth was an absolute necessity for the manufacturing of highly integrated devices. Dash developed this seeding technique first for the pedestal growth method and one year later in 1959 also for the Czochralski growth method.

Production of hyperpure CVD polysilicon

Wacker-Chemie started in 1953 the research for the production of semiconductor grade polysilicon and of float-zone silicon single crystals. The production began in 1958. At first, the techniques of Siemens for chemical vapor deposition and float-zone growth were used. In 1958, Wacker tested the possibility to make rod-shaped silicon single crystals by chemical vapor deposition according to the Siemens process. Using float-zone grown silicon single crystals of 6 mm diameter, they were successful in producing 50 cm long CVD silicon single crystals of ca. 20 mm diameter and of regular hexagonal cross section. The crystal axis was <111> and the six surfaces flats {110}. The CVD crystals had about the same dislocation density as the monocrystalline slim rod. However, the purity of these crystals was not as high as that of float-zone single crystals grown from the same CVD polysilicon because the CVD single crystal was not refined by segregation. Additionally, the production costs were high because of the low deposition rate. Therefore, the development for the growth of CVD silicon single crystals was stopped. Three years later in 1961, Wacker installed a large scale industrial production for hyperpure polycrystalline CVD silicon and silicon single crystals. The special feature of the new polysilicon production was that the trichlorosilane for the chemical vapor deposition was highly purified by intensive distillation. This new CVD polysilicon needed no further purification by zone refining for the growth of float-zone single crystals. From this time on, Wacker produced for a long period about 50 % of the world consumption of hyperpure polysilicon for the semiconductor industry.

Dislocation-free seeding at float-zone crystal growth

In the years 1961 to 1963, W. Keller and G. Ziegler from Siemens advanced Dash's seeding technique for the dislocation-free float-zone growth of silicon single crystals, [24]. Dash's technique was difficult to realize at float-zone growth, because here the seed crystal is situated below a small silicon melt hanging at the lower end of a melting silicon feed rod. On the other hand, float-zone growth offers an advantage which CZ growth cannot offer: When the FZ seed cone has

grown to a certain diameter, a supporting device moves up to come in contact with the seed cone. From now on, the whole weight of the crystal is carried by the supporting device and the stability of the seed neck plays no more a role. W. Keller patented several types of supporting devices. A secondary benefit of such a supporting is the possibility to grow always very thin and short seed necks which are the most successful in eliminating the dislocations and need the less time for seeding. Therefore, FZ growth has less problems with dislocation-free seeding for large crystals. At CZ growth of heavy crystals, the seed necks must be made rather thick and long, thick for holding the heavy weight and long for elimination of the dislocations. Thick seed necks are less successful in eliminating dislocations and the seeding must be repeated more often what costs time.

Improvement of the internal qualities of the silicon single crystals

Parallel to diameter and length of the crystals, also their internal properties must be changed and developed to fit the changing requests of the semiconductor device processes. When the dislocations were eliminated in the crystals the swirl-like microdefects occurred. They are agglomerates of self-point defects and could not form as long as there existed numerous dislocations in the crystals. In the seventies, experiments with nitrogen (N_2) additions to the argon atmosphere of float-zone pulling showed that both the self-interstitial type and the vacancy type microdefects were prevented if nitrogen concentrations of $(1\text{-}10)\text{x}10^{14}/\text{cm}^3$ are generated in the FZ crystals. Obviously, the nitrogen atoms form both with the self-interstitials and with the vacancies complexes which are not able to agglomerate to larger microdefects. The nitrogen-self-point defect complexes showed no detrimental effects. In CZ-Si, this beneficial effect of nitrogen is prevented unfortunately by the high oxygen concentration. At present, the most work is done with the reduction of the self-point defect originated defects in the large CZ-Si crystals, i.e. reduction of the number and size of the voids (agglomerates of vacancies) and of the OSF-ring defects (originally agglomerates of self-interstitials). In this field, the computer simulation of the diffusion, recombination, and agglomeration of the self-point defects were very useful.

Also in the seventies, the beneficial effects of oxygen in silicon for the manufacturing of semiconductor devices were detected:

a) Oxygen impedes the movement and multiplication of dislocations by the formation of Cottrell clouds at the dislocations and by the formation of oxygen precipitates.
b) The secondary defects of the oxygen precipitation, the small perfect and partial dislocation loops, act as effective gettering centers for fast diffusing impurities like Cu, Ni, and Fe.

IBM recognized the importance of oxygen for device manufacturing first, discernible at their publications: 1975, W.J. Patrick, S.J. Scilla, and W.A. Westdorp filed a patent for the adjustment of the oxygen content of growing CZ-Si crystals, [25]. T.Y. Tan and W.K. Tice were the first who cleared up by TEM the microscopic processes at oxygen precipitation, [26]. V. Cazcarra studied the different stages of oxygen precipitation and developed annealing processes, [27]. W.J. Patrick, S.M. Hu, and W.A. Westdorp investigated the effect of oxygen precipitation on MOS capacitors, [28]. Many other institutions and a huge number of authors studied and are still studying the influence of oxygen on silicon since this time.

Increase of crystal diameter and weight

The first CZ-Si crystals have been small in diameter, typically ½ inch, and their weight was between 50 and 200 g. In this time, one tried to grow the crystals in diameters which were same as that of the discrete devices. This means that, crystals of very small diameters had to be grown. Some patents were filed for the production of specially small diameter crystals. But soon it became clear, that also for discrete devices, it was more economical to produce larger single crystal slices from which many small slices could be drilled out. The tendency to larger crystal diameters increased when the simultaneous manufacturing of many semiconductor devices on one slice was developed, and it increased further when the integrated devices were invented in the early sixties by Texas Instruments. The simultaneous manufacturing of many devices on one wafer is much cheaper than the separate manufacturing of single devices. In some cases, more than 1000 small devices are manufactured on one wafer. The integrated devices have larger areas in most cases and large slices must be used to get 200 ore more of these devices on one wafer. Therefore, the largest wafers were used for the manufacturing of microprocessors until recently. Because of the immense cost pressure on the current DRAM production, this rule has changed, and the largest wafers, the 300 mm wafers, are now used first for the manufacturing of 64 MB DRAMs by Siemens.

The increase in wafer diameter and the corresponding typical crystal weights since 1952 are shown in the timetable below. 3 inch was the first worldwide standard diameter, chosen in 1973. The following wafer diameters were defined in millimeters. The future and possibly last larger diameter will be 400 mm or 450 mm. Crystals of such diameters show cooling strains near to the yield strength of silicon. In this case, the large temperature fluctuations of the large melts are very dangerous because they generate additional strain in the crystal which can push the total strain over the yield strength resulting in the formation of dislocations. The dislocation-free growth of such large crystals is therefore very difficult. There are two ways to overcome this problem:
a) Damping the melt flows with magnetic fields. b) Reduction of the melt height as far as possible and keeping the melt level constant by feeding the melt with silicon and dopant.

Timetable of silicon wafer diameter and crystal weight increase (weight: typical values):

Year	1950	1956	1962	1967	1972	1973	1980	1984	1988	1992	1997	2005
Diameter Measure	½ inch	1 inch	1.5 inch	2 inch	2.5 inch	3 inch	100 mm	125 mm	150 mm	200 mm	300 mm	400 mm
Weight, kg	0.05	0.4	1.2	2.5	6	12	24	38	65	110	200	350

The years shown in the table give the year when the diameter below was produced in larger numbers for the first time.

Present state of silicon crystal growth

The principle construction of a modern CZ-Si puller is shown in Fig. 6. Today, most of the growth furnaces show a heat shield between melt and crystal like in Fig. 7. Without such a heat shield, the growth of large crystals is difficult, or very difficult. The new pullers run fully automatically, i.e. after filling the puller with a new charge and closing, the process runs automatically until the

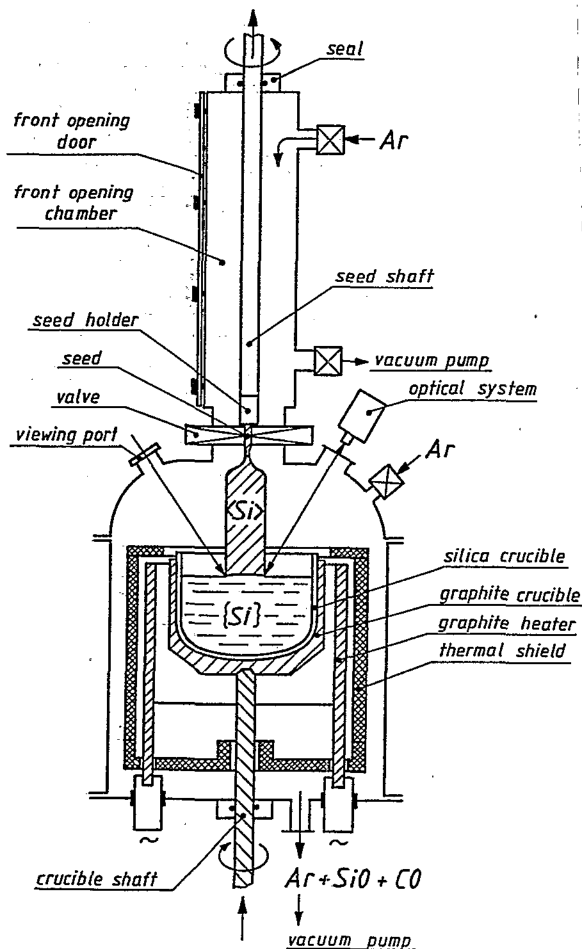


Fig. 6. Schematic of a modern CZ-Si single crystal puller for the growth of large crystals.

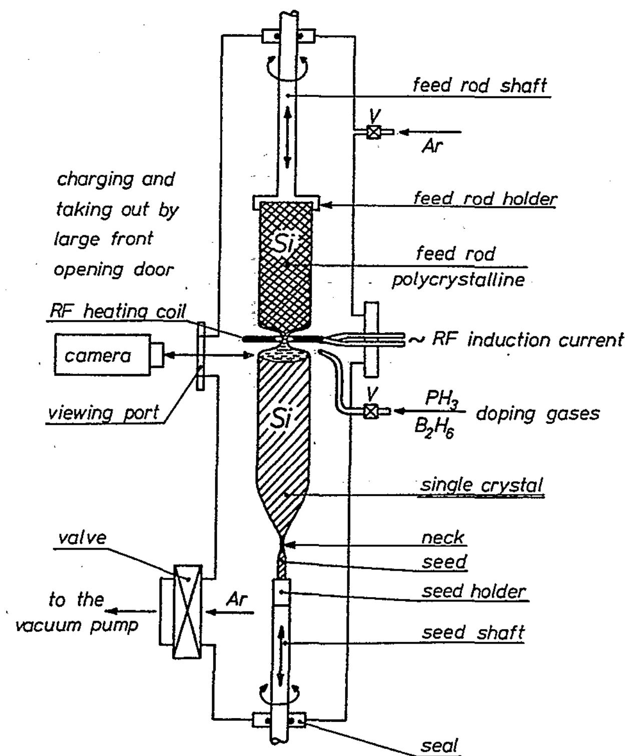


Fig. 9. Schematic of a modern FZ-Si single crystal puller for the growth of large crystals.

ventilation for reopening of the puller. One operator controls several pullers. The pullers are situated in clean rooms. At present, the largest pullers can take 300 kg Si melt for the growth of 300mm-diameter crystals and are usually equipped with magnets for damping of the melt and other purposes. Fig. 8 shows a CZ furnace with a "cusp" magnetic field. This type of magnetic field shows the best effects on the melt. For more information see [29, 30]. Owing to the strong depression in production and prices of semiconductor devices in the last years, the building of further factories for the production and use of 300mm wafers was delayed by most of the companies. The principle construction of a modern FZ-Si puller is shown in Fig. 9. At melt diameters larger than about 1 inch, the melt must be constricted to prevent the running down of the melt. A cylindrical shape of the melt is no more possible. The large melts show flat surface regions which are relatively the larger the larger the diameter is. The edge of the melt is kept together by its own surface tension and its meniscus has a height of ca. 5 mm, independently of the crystal diameter. Therefore, the diameter of a constricted FZ-Si melt can be enlarged arbitrarily. The main problems to be solved are the reduction of the very high cooling strains and to produce suitable large and crackfree polysilicon ingots. Up to 1999, the largest FZ-Si wafer diameter in the float-zone silicon production is 150 mm because there were no customers for larger FZ-Si wafers. This has changed recently, some customers want to have 200mm-FZ-Si wafers in future. Therefore, the development of the 200mm-FZ-Si growth process is at work.

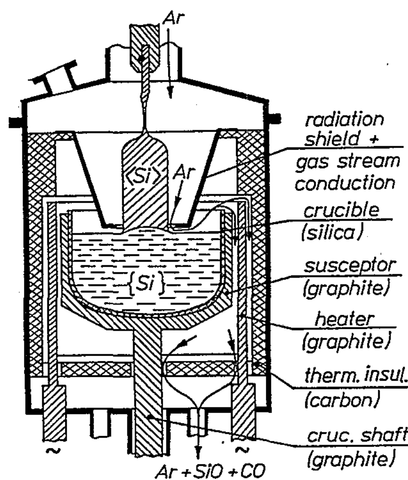


Fig. 7. CZ-Si furnace with a shield between melt and growing crystal for heat shielding of the crystal and conduction of the argon.

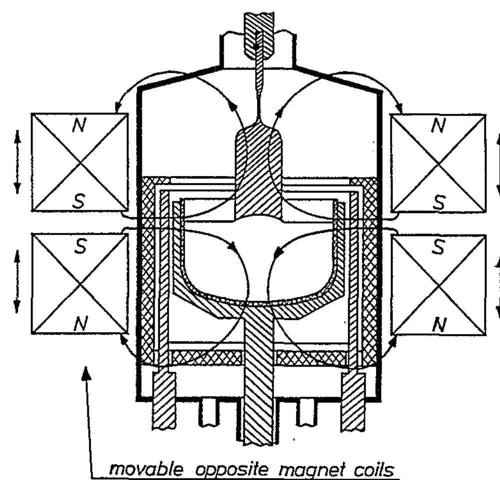


Fig. 8. CZ-Si furnace with two movable opposite magnet coils for damping of the thermal convection of the melt.

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