

Large-scale production of highly enriched ^{28}Si for the precise determination of the Avogadro constant

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Abstract

An attempt is described to replace the present definition of the kilogram with the mass of a certain number of silicon atoms. A prerequisite for this is that the Avogadro constant, N_A , is determined with a relative uncertainty of better than 2×10^{-8} . For the determination, silicon crystals are used. However, the difficulty arising thereby is the measurement of the average molar mass of natural Si. Consequently, a worldwide collaboration has been launched to produce approximately a 5 kg ^{28}Si single crystal with an enrichment factor greater than 99.985% and of sufficient chemical purity so that it can be used to determine N_A with the targeted relative measurement uncertainty mentioned above. In the following, the first successful tests of all technological steps will be reported (enrichment of SiF_4 , distillation into silane and chemical purification, chemical vapour deposition of polycrystalline ^{28}Si , floating zone growth of a dislocation-free single crystal) and new equipment for the production of high-purity ^{28}Si with an enrichment of not less than 99.99% will be described. All steps are well defined by a Technical Road Map (TRM28) and all key results are measured by new mass spectrometric, IR spectroscopic and other chemical and physical methods, such as Hall effect, photoluminescence, laser scattering and x-ray topographic methods (TRM for Analytical Monitoring and Certification, TRM28-AMC). The initial enrichment of the gas is $>0.999\,95$ and the depletion during the entire process is $<0.000\,05$. The isotopic homogeneity is checked by natural Si crystal growth and does, in the enriched sphere, not

exceed 5×10^{-10} , relatively. The C content of the final material is less than 10^{15} atoms cm^{-3} and the specific resistance is 400–1000 Ω cm.

Keywords: kilogram, Avogadro constant, silicon

(Some figures in this article are in colour only in the electronic version)

Dedicated to E O Göbel on the occasion of his 60th birthday

1. Introduction

The kilogram is the only base unit in the International System of Units (SI) which is still defined in terms of a material artefact. The main problems associated with this artefact are well known and can be summarized as follows:

- The prototype can be damaged or even destroyed.
- It is not stable (it accumulates foreign material and has to be cleaned before any use—with unknown consequences).
- It ages at an unknown rate (perhaps 50 μg change in mass within the past 100 years). This is because of possible instabilities of the international prototype based on observations of drift between the international and national prototypes over about 100 years.
- It limits the uncertainty of the kilogram in comparison to fundamental constants to a few parts in 10^8 at minimum.

As early as 1870, when James Clerk Maxwell [1] defined the well-known requirement that the physical units should not be founded on macroscopic quantities but on the properties of these ‘imperishable and unalterable molecules’, metrologists were called upon to investigate the possibilities of redefining the kilogram.

One of the possibilities discussed among metrologists today [2] is to trace back the unit of mass to an atomic mass, just as Maxwell would have done. The kilogram would then be defined as the mass of a fixed number of atoms of a specified entity. For this, the number of atoms in a macroscopic mass of a substance must be known with sufficient accuracy, so that the new mass scale agrees with the former one. The new definition of the unit of mass, the kilogram, could read as follows:

“The kilogram is the mass of N_{kg} unbound ^{12}C atoms at rest and in their ground state”

with

$$N_{\text{kg}} = \frac{\{N_{\text{A}}\}}{A_{\text{r}}(^{12}\text{C})} \times 10^3, \quad (1)$$

where N_{A} , $\{N_{\text{A}}\}$ is the numerical value, would become a defined constant whose value will be based on the best experimental determination and $A_{\text{r}}(^{12}\text{C})$ is the relative atomic mass of ^{12}C with $A_{\text{r}}(^{12}\text{C}) = m(^{12}\text{C})/m_{\text{u}}$, where m_{u} is the unified atomic mass unit.

This application of the Avogadro constant (a benchmark on the way towards the atomic definition, for details see [3]) presupposes a final measuring uncertainty of about 2×10^{-8} , which is a challenge for the experimental determination of the quantities involved, i.e. the macroscopic density, the isotopic composition and the unit cell volume of a silicon crystal. Using single crystals of natural Si, the value of the Avogadro constant has been obtained within a relative measurement uncertainty of 3×10^{-7} , but the uncertainty attained is close to a practical limit [4]. The combination of data from several independent

measurements of the unit cell and the molar volumes leads to a value for the Avogadro constant of $N_{\text{A}} = 6.022\,1353\,(18) \times 10^{23} \text{ mol}^{-1}$ [5].

A further attempt to reduce the uncertainty of the measured molar mass values (and hence of the value of N_{A}) was started in 2004 by fabricating a Si single-crystal sphere of $\geq 99.99\%$ enriched ^{28}Si , which has ^{29}Si and ^{30}Si abundances of the order of 0.005%. A relative combined measurement uncertainty of $\leq 1\%$ of each of these abundance-value corrections contributes a relative uncertainty of the molar mass value of the highly enriched ^{28}Si material of $\leq 3 \times 10^{-8}$. For the molar mass, this means that the calibrated measurement of the isotope amount ratios in Si of natural isotopic composition using synthetic isotope mixtures can be replaced by the measurement of (very) small ^{29}Si and ^{30}Si abundances in the highly enriched ^{28}Si . This results probably in (very) small corrections to the molar mass value of ^{28}Si , known with a relative combined uncertainty of $\leq 10^{-9}$. As these corrections will be measured, only the uncertainty of these (very) small corrections will enter into the uncertainty budget of the molar mass of the highly enriched ^{28}Si in the Avogadro crystal [6]. This approach is possible because a potential source of very highly enriched Si isotopes in Russia is being evaluated. From this enriched Si material, a 5 kg single crystal will be grown. It must be isotopically homogeneous, which also means that while gaseous SiF_4 (the form in which the Si is enriched in the isotope ^{28}Si) is transformed via several wet-chemical steps to polycrystalline Si (from which the single crystal is grown), the losses in the isotopic enrichment must be minimized. The requirements with regard to the chemical purity of this enriched ^{28}Si material are very stringent. A basic scientific and technical problem to be solved is to increase the chemical purity, in particular, in relation to the content of carbon and oxygen.

New analytical measurement techniques had to be developed and applied in order to be able to determine the required crystal properties with sufficient uncertainty, in particular, the determination of the carbon concentration in polycrystalline silicon below a level of $5 \times 10^{15} \text{ at cm}^{-3}$ at IChHPS using the laser ionization time-of-flight mass spectrometry (LIMS) and the isotope amount measurement of enriched silicon at IRMM using electron impact and thermal ionization mass spectrometry.

The availability of kilograms of high-purity mono-isotopic crystals is a breakthrough in the accurate determination of N_{A} . In fact, a precondition for determining the molar mass of the crystal with sufficient accuracy is that the enrichment in ^{28}Si is higher than 99.98%. Therefore, an international research cooperation has been set up to determine N_{A} via the measurement of the molar and atomic volumes of a ^{28}Si crystal with a target relative uncertainty of 2×10^{-8} . The growth of the first dislocation-free ^{28}Si single crystal by means

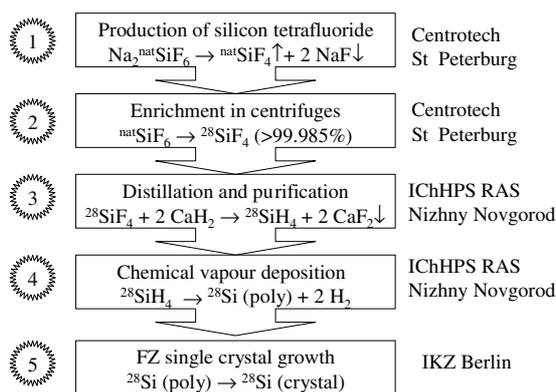


Figure 1. Production places and main production steps of ^{28}Si .

of the float zone (FZ) method was reported in [7]. Recently, the so-far purest single crystal of ^{28}Si has been grown, with concentrations of electrically active impurities $\leq 10^{15} \text{ cm}^{-3}$, oxygen $\leq 10^{15} \text{ cm}^{-3}$ and carbon $\leq 10^{16} \text{ cm}^{-3}$ and with a mass of 35 g [8]. The reported ^{28}Si enrichment was high (99.98%) but not high enough for an application in the Avogadro project. This reported technology is limited in mass by more than a factor of 10 compared to the necessary amount of 5 kg.

The presented work hereafter reports the technological steps and new equipment for the production and characterization of high-purity ^{28}Si with at least a 99.99% enrichment, including the FZ growth of a dislocation-free ^{28}Si crystal which has a mass of 200 g and will serve as a basis for the planned 5000 g crystal.

2. Experimental details

The key technological steps in the production of isotopically enriched silicon, the gas centrifugation for the isotope separation in the form of silicon tetrafluoride (SiF_4), the transformation of SiF_4 into the monosilane gas SiH_4 , followed by low-temperature rectification and the deposition of polycrystalline silicon (by thermal decomposition of silane) in the form of silicon rods which are then used as a starting material for FZ single crystal growth are shown schematically in figure 1. The Technical Road Map [9] for the production of ^{28}Si single crystal precursors (TRM28) describes in part 1 all important operations, equipment and products necessary to grow a perfect crystal which meets the targets of the International Avogadro Project (TRM28OEP). In part 2, the analytical monitoring of the isotope enrichment, the chemical purity and the measurements of the crystal perfection together with a certification chain are summarized as a guideline (TRM28AMC). In part 3, the sample identification system (TRM28SIS) is discussed, together with the code system and the table of sample traceability. The sample identification system enables us to trace back any sample of the Si material through the entire technological chain TRM28OEP and to assign the measurement results distinctively in the TRM28AMC for all intermediate technological stages and their products. In table 1, a detailed flow chart of the Technical Road Map is given.

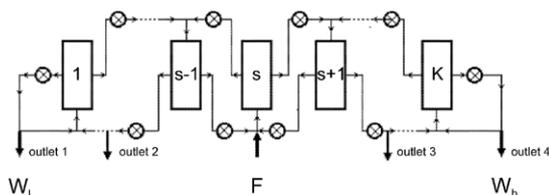


Figure 2. Centrifuge cascade of Centrotech, especially designed for the enrichment of ^{28}Si for the Avogadro project. W_l , W_h : outlets of light and heavy fraction of cascade, respectively; F : feed flow (inlet point ‘S’); \otimes : devices for regulation and control of the flow system; 1, K: ‘accumulator’ of light/heavy impurities of cascade.

2.1. Silicon tetrafluoride

SiF_4 as the starting substance for the ^{28}Si separation was prepared from Na_2SiF_6 powder as follows:



The lightest $^{28}\text{SiF}_4$ fraction was separated by means of the ultra-centrifugation [10, 11] method in two stages using cascades of gas centrifuges:

First stage—the optimization of technology of enrichment of the ^{28}Si isotope and modernization of the separation unit to improve the chemical purity of $^{28}\text{SiF}_4$.

Second stage—the increasing of separation capacity by up-scaling.

During the first stage, significant differences between theoretical and practical values of isotope abundance of ^{28}Si in the product outlet of cascade were determined, e.g. instead of a theoretical value of 99.99% for ^{28}Si we obtained in practice 99.94%. This deviation was caused by compounds such as $\text{Si}_2\text{F}_6\text{O}$, SiF_3OH and others, which are impurities introduced in the feed flow. In order to separate the impurities from the product ($^{28}\text{SiF}_4$), specially interconnected cascades were constructed and built-in. As the result of these works, a ^{28}Si enrichment of 0.999 9661(46) was achieved [12]. At the second stage, to increase the accuracy of maintaining the mode of enrichment of the ^{28}Si isotope, additional investigations have been carried out. Using special control systems, the long-time stability of maintaining the ^{28}Si isotope at the product outlet of cascade was $\pm 0.001 \text{ l d}^{-1}$ over more than 6 months.

Also, at the second stage a cascade was modernized for increasing the productivity and efficiency of the separation.

The number of gas centrifuges was doubled. The basic design is shown in figure 2. The configuration of an ‘ideal cascade’ for the separation of multi-isotope gases was implemented. This configuration is designed in such a way that a mixing of flows having different ^{28}Si isotopes in the cascade is ruled out. A new arrangement of a cascade of 230 centrifuges was chosen to achieve a higher enrichment and higher productivity. The measured averaged final isotope enrichment of $^{28}\text{SiF}_4$ (7294 g ^{28}Si) is 0.999 928, as shown in figure 3.

2.2. Silane

For the production of high-purity silicon, the hydride method was used. As a first step, $^{28}\text{SiF}_4$ was transformed to monosilane

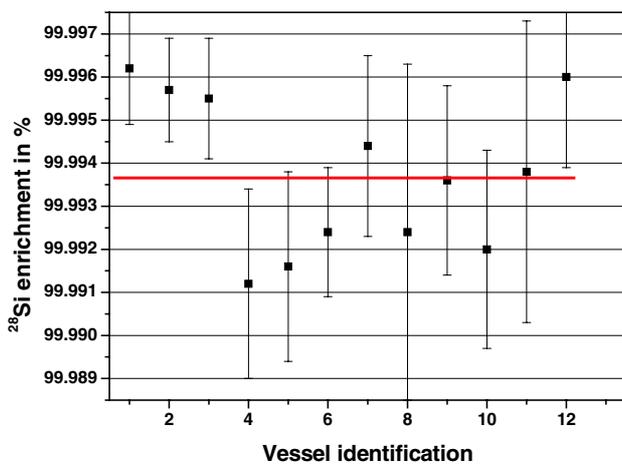
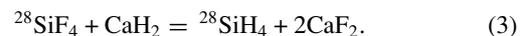
Table 1. Summary of the technical road map (TRM) for the production of Si-isotope single crystals, for AVOGADRO spheres (status 2006-01-31).

| Analytical Monitoring | | Main Stream of Operations (Op), Equipment (Eq) and Products (Pr) | Tributary products (tp) | Responsible Institute for Production/ For measurements |
|---|---|---|---|---|
| Chemical impurities | Isotopic impurities | | | |
| C-LMsolid | | Op1: Chemical purification Na_2SiF_6 | | CT SPb |
| | | Op2: Pyrolyze in ZT-Reactor Pr2: SiF_4 | | CT SPb |
| C-IRgas, C-GC C-IC, C-AE | I-LMgas, GMS I-TIMS | Op3: Isotope Enrichment of: $^{28}\text{SiF}_4$ in new centrifuge-cascade in CT | | CT SPb/ IChHPS, IRMM |
| | | ↓ | tp5: Glowing CaH_2 | IChHPS NNov |
| | | Op4: Silanization: $^{28}\text{SiF}_4 + \text{CaH}_2 \rightarrow$ $^{28}\text{SiH}_4 + \text{CaF}_2$ | | IChHPS NNov |
| | | ↓ | | |
| C-IRgas, C-GC C-IC, C-AE | I-LMS, MS GMS I-TIMS | Op5: Purification, Rectification | | IChHPS NNov/ IChHPS |
| | | ↓ ↓ | tp7: Pulling of slim rods for Op7A | IKZ Berlin |
| C-TLMR(O, H) C-IRgas | I-LMsolid, I-TIMS I-MS GMS | Op7: Pyrolytic decomposition on Si slim rods, with new equipment | | IChHPS NNov/ IChHPS, IRMM |
| | | ↓ | Op8: Homogenizing and purification by CZ-growth from coated crucible and dross removing | IKZ Berlin |
| | | ↓ | tp9: Coating of crucible with $^{28}\text{SiO}_2$ | |
| | | ↓ | tp10: Preparation of oriented seed crystals | |
| | | Op9: Purification by FZ crystallization (crucible free) | | IKZ Berlin |
| | | ↓ | | IKZ Berlin |
| C-LMsolid-RS C-TLMRsolid, C-IRsolid | I-LMsolid, I-MS (SSMS+GMS) I-TIMS | Op10: Final crystallization in defined direction and specified dimensions | | IKZ Berlin / PTB, IChHPS IRMM |
| | | ↓ | | |
| | | Op11: cut the crystal for sphere | | IKZ Berlin |
| S- MD, S-LP, S-SX | | SPECIAL AVOGADRO PROCESSING | | PTB, NIST, ... |
| | | Op12: Application and Recycling of residual ^{28}Si . | | CT- SPb VITCON Jena |

Part 1 Operations, Equipment and Products (red).

Part 2 Analytical Monitoring (yellow).

Part 3 Product Certification (green), Tributary Products (brown).

**Figure 3.** Enrichment of $^{28}\text{SiF}_4$ gas over a production period of 6 months. Total amount of $^{28}\text{SiF}_4$ is 27.071 kg (^{28}Si : 7.2883 kg). The error bars represent $k = 2$ measurement uncertainty of the measurement certificates. $^{28}\text{SiH}_4$ using the chemical reaction with calcium hydride:

The synthesis was carried out in the flow-through mode. The mixture of hydrogen and $^{28}\text{SiF}_4$ was passed through the reactor with fine-dispersed calcium hydride. The temperature of the synthesis was $\sim 180^\circ\text{C}$ and the conversion efficiency exceeded 90%. The reaction was carried out without organic solvents to prevent silane contamination with carbon.

The content of hydrocarbons in silane, measured by gas chromatography, corresponds to their concentration in tetrafluoride (table 2, second column).

The synthesized monosilane was mainly contaminated by fluorine-containing compounds (fluorine-siloxanes) and light hydrocarbons $\text{C}_1\text{-C}_4$. The monosilane was ultra-purified by sequential cryofiltration and rectification. Cryofiltration preliminarily purifies the monosilane from low-volatile impurities at a low boiling temperature and from small particles. Hydrocarbons were removed by rectification in a stainless steel column with the feeding reservoir placed in the

Table 2. Hydrocarbon content in $^{28}\text{SiH}_4$ before and after purification.

| Hydrocarbons | Before purification ($\mu\text{mol mol}^{-1}$) | After purification ($\mu\text{mol mol}^{-1}$) |
|--|--|---|
| CH_4 | $(2.3 \pm 0.3) \times 10^{-3}$ | $<4 \times 10^{-6}$ |
| C_2H_6 | $(5.3 \pm 0.5) \times 10^{-3}$ | $<2 \times 10^{-6}$ |
| C_2H_4 | $(4.9 \pm 0.5) \times 10^{-3}$ | $<2 \times 10^{-6}$ |
| C_3H_8 | $(1.5 \pm 0.2) \times 10^{-4}$ | $<2 \times 10^{-6}$ |
| C_3H_6 | $(2.0 \pm 0.2) \times 10^{-4}$ | $<2 \times 10^{-6}$ |
| <i>n</i> - C_4H_{10} | $(1.3 \pm 0.3) \times 10^{-4}$ | $<2 \times 10^{-6}$ |
| <i>iso</i> - C_4H_{10} | $(2.1 \pm 0.3) \times 10^{-4}$ | $<2 \times 10^{-6}$ |

centre of the column in the periodic-mode operation. The fractions containing compounds with boiling points lower or higher than that of silane were removed simultaneously from the top and bottom of the column, respectively. The concentration of C_1 – C_4 hydrocarbons in the selected fractions was monitored by gas chromatography. Table 2 (third column) shows the results of the analysis of $^{28}\text{SiH}_4$ after the process of purification. One can see that the concentration of hydrocarbons in the monosilane is reduced by more than a factor of 100 by ultra-purification.

2.3. Polycrystalline silicon

Polycrystalline silicon was produced by the thermal decomposition of monosilane in a specially designed vertically arranged single-rod set-up. The shape of a single rod made it possible to use the maximum of the deposited material for the single crystal growth by means of the FZ method. To start the silane deposition process, a ^{28}Si slim rod was used with an enrichment of 99.99% previously grown by the pedestal technique from another ^{28}Si crystal as the starting material. The diameter of the slim rod was 7 mm and the resistivity exceeded $500 \Omega \text{ cm}$. The slim rod was fixed between molybdenum contacts and was heated by a direct current. The upper contact was movable in the axial direction to compensate for the linear thermal expansion of the rod during heating up. The operating rod surface temperature of 800°C was measured by means of an optical pyrometer and adjusted by automatic control of the heating power. In order to hold the surface temperature constant, the heating power was increased during the process. The silane feed rate was chosen in such a way that a heterogeneous silicon deposition was achieved. As the diameter of the polycrystalline Si rod increases during the process, the supply rate of silane was continuously increased, thus stabilizing the radial deposition rate at 0.05 mm h^{-1} .

With this technique, a polycrystalline silicon rod with a diameter of 24 mm and a mass of 440 g was produced; the silane conversion efficiency was 95%. Figure 4 shows the as-deposited poly- ^{28}Si rod in the reactor.

A model experiment was performed in the same reactor using silane of natural isotope composition in order to investigate the expected but unwanted isotope separation effect due to thermal diffusion in the gas phase during the deposition. Because of this effect, the concentration of the heavier $^{29}\text{SiH}_4$ and $^{30}\text{SiH}_4$ molecules should rise at the bottom of the reactor. A difference of 0.000 000 93 of the ^{28}Si enrichment was observed along the polycrystalline rod (length 80 cm) for the natural

**Figure 4.** Polycrystalline silicon rod Si28-9.1Pr7, see table 1, deposited from SiH_4 . The crystal length is approximately 600 mm and the diameter is 40 mm.

abundance of 92%. Up-scaled to an enrichment of more than 99.985% ^{28}Si for the Avogadro project, the isotopic inhomogeneity of the materials processed of about 10^{-10} is negligibly small.

2.4. Single crystal growth

The deposited polycrystalline ^{28}Si rod was the starting material for the FZ crystal growth. This is very suitable for the single crystal growth of isotopically enriched silicon compared with the Czochralski method that uses a fused silica crucible containing natural silicon to dilute the isotopic enrichment and an additional carbon contamination of the ^{28}Si melt.

The polycrystalline Si rod (feed rod) was etched in $\text{HNO}_3:\text{HF}$ to remove the fine Si dust from the surface that can impact the FZ growth. A seed crystal with an orientation of $\langle 100 \rangle$ was prepared earlier by the pedestal growth method from a feed rod of a previous charge of 99.986% ^{28}Si . The crystal growth was performed in Ar atmosphere under conventional growing conditions. A dislocation-free ^{28}Si single crystal with a diameter of 30 mm was grown in the first run confirming the quality of the polycrystalline material (figure 5(a)). The electrical resistivity of the material was $\geq 200 \Omega \text{ cm}$ and of the n-type, corresponding to a phosphorus net concentration of $2.2 \times 10^{13} \text{ cm}^{-3}$.

To determine the impurity content and the ^{28}Si enrichment in the single crystal, four wafers were cut from the beginning of the cylindrical part of the rod. The results showed an oxygen concentration of $2.8 \times 10^{15} \text{ cm}^{-3}$, a carbon concentration

Table 3. Isotope enrichment in the different technological steps.

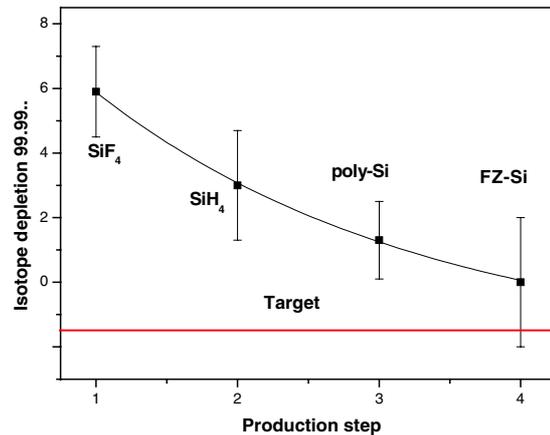
| Enrichment | Isotope | | |
|-------------------|--|--|--|
| | ^{28}Si (charge 9.1 of ^{28}Si production) | ^{29}Si (charge 2 of ^{29}Si production) | ^{30}Si (charge 2 of ^{30}Si production) |
| In SiF_4 | 0.999 959 (14) ^a , 0.999 9661 (46) ^b | 0.995 76 (105) ^a | 0.998 29 (60) ^a |
| In SiH_4 | 0.999 930 (17) ^a | | |
| In poly-Si | 0.999 905 (22) ^a | 0.994 87 (45) ^a | 0.997 347 (525) ^a |
| In Si-crystal | 0.999 900 (38) ^a , 0.999 901 27 (60) ^b | 0.992 39 (23) ^a | 0.997 22 (22) ^a |

^a Measured at IChHPS.^b Measured at IRMM.**Figure 5.** ^{28}Si single crystals, FZ-grown from the polycrystalline rod Si28-9.1Pr7, (a) after one FZ run (crystal Si28-9.1Pr10) and (b) after seven FZ runs (crystal Si28-9.1Pr11); see the text. Scale mark: 20 mm.

of $4.85 \times 10^{15} \text{ cm}^{-3}$ and a boron concentration of $1.3 \times 10^{13} \text{ cm}^{-3}$, which are partly higher than the concentrations required for the Avogadro crystal.

Taking into account the well-known purification effect of FZ growth based on the impurity segregation during the growth process, seven additional growth runs were carried out to achieve the requirements of the project. Because the segregation effect does not work in the case of oxygen, five runs were made in vacuum followed by two runs in argon atmosphere. On the basis of the distribution coefficient of carbon in silicon ($k_0 = 0.07$) and the carbon concentration in the ^{28}Si crystal after the first run, it was estimated that after seven additional runs the carbon concentration should be lower than $2 \times 10^{15} \text{ cm}^{-3}$ in about two-thirds of the crystal volume.

Figure 5(b) shows the dislocation-free ^{28}Si single crystal with a diameter of 29.5 mm after the last growth run. The crystal is of the p-type, with a resistivity of 400–1000 $\Omega \text{ cm}$. A change of the conductivity type—from n-type to p-type—is caused by more effective segregation and evaporation of phosphorus ($k_0 = 0.35$) in comparison to boron ($k_0 = 0.8$), the

**Figure 6.** ^{28}Si isotope depletion during the entire production step of charge 9.1. The error bars represent the $k = 2$ uncertainty of the measurement certificates.**Table 4.** Results of the chemical measurement of the main impurities for the single crystal Si28-9.1Pr11. For estimate of the P content, see the text.

| Impurity | Content of impurity ($\times 10^{15} \text{ atoms cm}^{-3}$) measured by | |
|----------|--|--|
| | IR-spectroscopy (Si28-9.1Pr11.2.3) | Laser mass spectroscopy (Si28-9.1Pr11.3.1) |
| C | <0.5 | <0.14 (6) |
| O | 1.66 (20) | 3.0 (5) |
| B | 0.013 (7) | |

main doping impurities in silicon. From the observed change in the conductivity type in combination with additional FZ runs, a residual P concentration well below $1.2 \times 10^{13} \text{ cm}^{-3}$ can be derived. Both B and P concentrations are too low to have a significant influence on the determination of the Avogadro constant.

3. Results and discussion

For the certification of the ^{28}Si single crystal shown in figure 5(b), the measurement of its isotopic composition, as well as of the oxygen and carbon contents limiting the chemical purity, was carried out. The samples for this measurement were cut from the beginning of the cylindrical part of the crystal.

The isotope measurements of the grown single crystal were made by laser mass spectrometry (LIMS) at the IChHPS RAS and not only by electron impact GAS mass spectrometry (EIGSM) but also by thermal ionization mass spectrometry

(TIMS) at IRMM. The results of the isotopic analysis (table 3 and figure 6) show that the content of the ^{28}Si in the crystal exceeded 99.99%. For completeness, the enrichments for the minor isotopes ^{29}Si and ^{30}Si for different production steps are also given [13]. To verify the oxygen and carbon concentrations in the ^{28}Si single crystal, IR spectroscopy (IChHPS RAS and PTB) and laser ionization time-of-flight tandem mass reflection of IChHPS were used. The results given in table 4 show that the crystal grown is at its highest purity with respect to electro-active impurities.

4. Conclusion

The technique proposed for the production of high-purity ^{28}Si makes it possible to produce before the end of 2006 a high-purity single crystal with a chemical and isotopic purity meeting the requirements of the Avogadro project.

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