Semiconductor Crystal Growth under the Influence of Magnetic Fields

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The recent development of semiconductor crystal growth focusses on increase of process efficiency and simultaneous improvement of crystal quality. For improved crystal quality, an exact and permanent control of the melt flow is a crucial parameter. To achieve larger crystals, the melt volume must be increased markedly resulting in disadvantageously changed melt convection. In the case of Czochralski growth, the flow can even become turbulent. This changed flow can disturb the single crystal growth and may give rise to dopant inhomogeneities within the crystal. To effectively influence melt flow and hence to improve growth conditions, magnetic fields can be applied. Mostly, steady magnetic fields (SMF) are applied in industrial scale to damp melt flow oscillations. However, compared to SMF the application of non-SMF proves to be also very promising since significantly lower induction causes similar effects in the melt. An overview on magnetic field features with the focus on achievable results under the influence of traveling magnetic fields is given.

1. Introduction

Today, the demand of industrial semiconductor crystal growth is directed at enhancing the yield and simultaneous improving the crystal quality. At present, major melt growth methods are crystal pulling (better known as Czochralski [CZ]), unidirectional solidification (in the main variants: Bridgman, vertical gradient freeze [VGF], heat exchange technique) and zone melting. By inducing a well-controllable flow in the melt. Depending on the direction of the magnetic field movement one can either damp or accelerate the melt flow. Due to the controlling of the forced convection, a favorable mixing or a stabilized mass flow can be induced in the melt. This concept is rather known from the metal casting industry. Mullin and Hulme proposed the use of magnetic fields (TMFs) with different directed Lorentz forces \( F_L \) induced by relatively low magnetic inductions \( B \) in the range of mT proved to be a very useful tool for contactless melt stirring and s/l interface shaping of semiconductors.

2. Classification of Magnetic Fields in Crystal Growth

Magnetic fields can be distinguished into steady and nonsteady magnetic fields. The steady magnetic fields (SMF) can be induced quite simply by a permanent magnet or by a DC operated coil. Nonsteady magnetic fields (NSMF) require a more sophisticated current control with at least an AC operation power supply.

Into moving semiconductor melts, such as metals and several ionic fluids showing electrical conductivity \( \sigma \), a current is induced by a SMF, described by the Lorentz force density \( F_L \). This current is directed opposite to the melt flow, which can be used to damp natural convection and their fluctuations in the melt. Thus, especially turbulent melt flow can be avoided reducing or even preventing corresponding doping striations in the grown crystal. First reports about successful use of SMFs in crystal growth were given independently by Utech and Flemings and Chedzey and Hurle in 1966.

NSMF have the potential to influence heat and mass transfer by inducing a well-controllable flow in the melt. Depending on the direction of the magnetic field movement one can either damp or accelerate the melt flow. Due to the controlling of the forced convection, a favorable mixing or a stabilized mass flow can be induced in the melt. This concept is rather known from the metal casting industry. Mullin and Hulme proposed the use of NSMFs for stirring of semiconductor melts during zone refining (ZF) already in 1958. The stirring efficiency of radio frequency (RF)-induced Lorentz forces at floating zone (ZF) growth of germanium crystals was studied by Gondi and Scacciati in 1961.
At the same time, Johnston and Tiller applied electromagnets for mixing of the molten part during unidirectional solidification of Pb-Sn alloys. They proposed to stabilize the interface morphology and to improve the control of axial segregation by reducing the danger of constitutional supercooling. Nowadays, several NSMF techniques in crystallization processes are used, such as rotating magnetic fields (RMF), alternating (pulsing) magnetic fields (AMF), or TMF. In Figure 1 the most popular variants of magnetic fields are summarized schematically.

One further opportunity approach is an internal heater-magnet module (HMM)—KRISTMAG—replacing the usual heater close to the crucible. The HMM features a special heater geometry in combination with a particular power supply. It can provide simultaneously direct current (DC) and alternating current (AC) in order to generate thermal and magnetic fields, here TMFs. Amplitude, frequency, and phase shift of the three-phase current are freely adjustable and combined with a DC component to control the dynamics of the crystallization process effectively. The design of HMM, its position relative to the melt, and the choice of electromagnetic parameter depend on the growth method. Some selected results will be presented hereafter.

3. Application of Steady Magnetic Field

The application of SMFs for CZ growth of silicon crystals was introduced by Hoshi et al. and Suzuki et al. They showed that magnetic fields could improve the crystal quality as they suppress the disturbing convective fluctuations very effectively. Additionally, the impurity transport in the melt could be minimized and, thereby, Si crystals with significantly reduced oxygen concentration could be obtained. Such results triggered enormous research activity on crystal growth under the influence of various magnetic fields and led to the first applications of magnetic CZ methods under industrial conditions. Terashima and Fukuda grew the first semiconductor compound crystals (GaAs) using magnetic liquid encapsulated Czochralski (MLEC) method. A significant damping of the temperature oscillation was observed. Later, Hofmann et al. demonstrated the SMF efficiency for high-pressure LEC growth of Fe-doped InP. Bliss et al. succeeded in 1991 to grow twin-reduced InP crystals by using magnetic melt control. The tests to grow dislocation-
free 450 mm silicon crystals from vast melt volumes of 400 kg with strong flow turbulences was only possible by using a strong superconducting SMF. Cröll et al. have studied the influence of magnetic fields on the FZ process for silicon. SMFs were also applied to VGF to grow nearly striation-free GaAs single crystals.

In the course of the developments, three different types of SMF can be distinguished: vertical (axial) (VMF), horizontal (transverse) (HMF), and cusp (CMF) for semiconductor materials (see Figure 1). The growth under SMFs has been tested for nearly all melt growth methods and numerous electroconducting materials. Besides silicon different other materials are industrially grown using magnetic fields for melt motion control. However, all types of SMF can damp melt motions but cannot accelerate the flow. From a technological point of view, the main problem of SMFs proves to be the low-cost generation of high-intensity magnetic fields. To obtain the necessary field strength special, often helium-cooled, magnets are required. For instance, at CZ Si growth the magnets have to be large enough to enclose the whole growth chamber and strong enough to induce a magnetic field over a distance larger than 1 m. Both VMF and HMF show favorable effects in different crystal growth techniques. But the field strength required for significant damping of the melt flow instabilities may break the symmetry of the melt flows. The symmetry is advantageous for growth stability and homogeneity of the crystal. The more favorable CMF overcomes this problem. The so-called cusp fields are generated by a pair of Helmholtz coils operating with opposed current directions. As a result, the damping of undesirable flow perturbations could be minimized more effectively in higher melt flow symmetry. Such a configuration combines the advantages of HMF and VMF and nearly symmetric axial forces perpendicularly to the melt–crucible interface are applied. For growing silicon crystals, the required typical magnetic field strengths of CMF is tens of mT and one order of magnitude higher than those used for VMF or HMF.

Nevertheless, all static magnetic fields do not always help to control hydrodynamic instabilities totally. As an example, Hirata et al. reported that temperature fluctuations are at least translated into periodic oscillations when the applied magnetic strength is too small. According to Gelfgat and Gorbunov, instabilities under magnetic fields may also be affected by the con-

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**Figure 4.** Images of a) Ge single crystal with 4-inch diameter and mass of 5 kg and b) mc silicon ingot for photovoltaic of size G5 and mass 640 kg, both grown in HMM configurations.

**Figure 5.** Comparison of the interface shape in longitudinal cuts of as-grown Ge crystals revealed by LPS striation analysis: a) conventional VGF without HMM and b) grown with HMM.
Figure 6. Striation analysis on microscopic scale taken from longitudinal cuts of different as-grown 4-inch VGF Ge crystals grown a) without magnetic field, b) under nearly optimized TMF parameters, and c) at overcritical TMF conditions.

4. Application of Heater-Magnet-Module-Induced TMF

NSMFs attract increasing attention for growth of single crystals with improved quality and are meanwhile widely used. In particular, the well-defined flows generated by relatively low nonsteady induction forces improve the temperature and concentration distributions considerably. Furthermore, the required induction intensities are about one order of magnitude lower compared to SMFs. Over the last years among the NSMFs the TMFs achieved increased importance. Therefore, in the following the results of TMF application will be described in more detail.

TMFs are usually generated by applying alternating currents (ACs) to a number of vertically stacked coils. As a result, a meridional traveling Lorentz field is induced within the enclosed conducting melt. The direction (up- or downward), frequency $f$, phase shift $\phi$, and amplitude $I$ of the field line can be controlled very conveniently. A conventional TMF arrangement may consist of three coils in delta connection arrangement. By supplying the standard three-phase AC, a frequency of $f = 50$ Hz and a constant phase shift of $\phi = 120^\circ$ magnetic fields are automatically obtained and invariable. In the past years, research has been concentrated on TMF application in VB and VGF arrangements for fundamental studies in metallic alloys,[30] semiconductors Ge[31] and Si,[34] as well as compound semiconductors, such as GaAs[32] and InP.[33] Also, the CZ growth of silicon crystals under TMF has been investigated.[35] It has been shown that the application of TMF is very favorable for a defined control of temperature distribution in order to control s/l interface shape. Since, for example, the melt flow pattern can be influenced the incorporation of oxygen in the crystal can be reduced.

Usually, a conventional TMF arrangement is based on AC coils placed outside the furnace (see Figure 2a). However, such an arrangement suffers from strong shielding effects by the metallic growth vessel and inside heater windings. Thus, a relatively high magnetic induction is required. Therefore, external TMF magnets are quite expensive and energy consuming.[36] A significant cost reduction can be achieved when the TMF generator is placed as close as possible to the melt. The most efficient approach was proposed within the framework of the KRISTMAG project, where a consortium of different research institutions and industrial partners developed the so-called HMM (which combines the simultaneous operation with direct current [DC] and alternating current [AC]) that enables decoupled generation of...
heat and TMF.[3] The direction and magnitude of the TMF can be adjusted. The ranges are AC/DC ratio 0–100 %, frequency 10–600 Hz and a phase shift between the heater coils of 0–360°. The suitable parameter field is estimated with the help of numeric simulations and according to the desired growth conditions. Hence, the acting Lorentz forces are very variable and ensure the control of melt flow over a wide range. Such an HMM can be used to improve the crystal quality by: i) increasing or decreasing the melt mixing, ii) controlling the s/l interface shape and morphology, and iii) damping possible temperature oscillations.

Figure 2b shows a sketch of an HMM in a VGF arrangement. The HMM consists of multiple coils and replace the standard “picket fence” heater.

Figure 3a,b shows drawings of a conventional “picket fence” formed heater and a HMM configuration consisting of three coils, respectively.

The KRISTMAG concept is applicable for various materials, like Ge, Si, and GaAs, and has been used in numerous growth techniques, such as CZ,[17] LEC,[18] VGF,[19,20] directional solidification,[21,22] and liquid phase epitaxy (LPE).[23] HMMs have been designed and realized in various growth geometries and scales for the crystallization in single as well as multicrystals. Meanwhile, it was transferred from laboratory to industrial scale.[24]

Figure 4a shows an image of a 4 inch Ge VGF single crystal grown in an HMM equipped furnace at IKZ and in Figure 4b a multicrystalline (mc) G5 Si ingot with a weight of 640 kg is presented. To achieve a favorable, nearly flat up to slightly convex growing s/l interface shape, the TMF parameters have been optimized numerically. The resulting temperature isotherms have been visualized for validation via striations by lateral photo voltammetry simulations and according to the desired growth conditions. Hence, the acting Lorentz forces are very variable and ensure the control of melt flow over a wide range. Such an HMM can be used to improve the crystal quality by: i) increasing or decreasing the melt mixing, ii) controlling the s/l interface shape and morphology, and iii) damping possible temperature oscillations.

Figure 5 shows the visualized interface deflections after etching longitudinal cuts of two GaAs crystals, which were grown with increased growth rate and different magnetic field strength to illustrate the opportunities and challenges of process improvement. Basis has been a set of growth conditions providing single crystals with a growth rate of 2 mm h\(^{-1}\). Increasing the growth rate to 4–5 mm s\(^{-1}\) leads to polycrystalline growth and pronounced s/l interface concave bending (Figure 7a). The GaAs crystal in Figure 7b was grown under equal thermal conditions with an average growth rate of 5 mm h\(^{-1}\) but with increased magnetic field strength. The bending of the interface was significantly reduced and a single crystal with a good crystal quality was obtained.

In addition to the above demonstrated increased growth rate and, thus, reduced process time a multi-crucible HMM was developed (note that the crystal growth in multi-crucible setups without magnetic fields were already known[25,26]). The challenge of the development of a multi-crucible HMM consists in the required nearly symmetric distribution of the temperature and Lorentz force density to get coincident seeding and interface positions in every crucible as well as symmetric interface shapes to avoid asymmetric stress distributions in all growing crystals. The first published setups were still deficient in this point. In the further course of development the 3D simulations indicated that the multi-crucible heater-magnet module (Figure 8a) allows the realization of nearly simultaneous temperature and magnetic flux density distributions in all crucibles,[20] as can be seen in Figure 8b,c. With such optimized multi-crucible HMM it was possible to grow several single crystals with comparable qualities at the same time.

We should highlight here that a strong continuous interchange between numeric simulations and corresponding experiments is needed to develop both the configuration and a suitable TMF parameter field.
5. Conclusion

The main challenges of present crystal growth development are the increase of the process yield and the reduction of production cost paired with the demand of improved crystal quality. The use of magnetic fields has been investigated intensively over the last decades and extended the parameter field to influence the melt flow essentially. The application of TMFs is of increased importance even for such a mature growth technology used for semiconductor materials, such as Si, Ge, and GaAs. A very promising approach to realize proper Lorentz forces and hence to control melt motions is the application of the KRISTMAG concept.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

Czochralski growth, directional solidification, magnetic fields, semiconductors, single crystals, vertical gradient freeze technique

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