N92-27794

WIDE GAP, PERMANENT MAGNET BIASED MAGNETIC BEARING SYSTEM

Karl Boden
Institut für Grenzflächenforschung und Vakuumphysik
Forschungszentrum Jülich, Postfach 1913
D-5170 Jülich
Germany

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ABSTRACT

The unique features and applications of the presented electro-permanent magnetic bearing system essentially result from three facts: (1) The only bearing rotor components are non-laminated ferromagnetic steel collars or cylinders; (2) all radial and axial forces are transmitted via radial gaps; (3) large radial bearing gaps can be provided with minimum electric power consumption. The large gaps allow for effective encapsulation and shielding of the rotors at elevated or low temperatures, corrosive or ultra clean atmosphere or vacuum or high pressure environment. Two significant applications are described: (1) A magnetically suspended X-ray rotary anode was operated under high-vacuum conditions at 100 KV anode potential, 600°C temperature at the rotor collars and speed 18000 r.p.m. with 13 mm radial bearing gap. (2) An improved Czochralski-type crystal growth apparatus using the hot-wall-method for pulling GaAs-single-crystals of low dislocation density. Both, crystal and crucible are carried and transported by magnetically suspended shafts inside a hermetically sealed housing at 800°C shaft and wall temperature. The radial magnetic bearing gap measures 24 mm.

1. INTRODUCTION

Drive shafts are commonly used in mechanical applications, where linear and/or rotating motion of the shaft is necessary to perform a task. A variety of guide and drive means are developed for effecting the desired relative longitudinal and/or rotary movements of workpieces along a predetermined axis. But there are a lot of problems which are not satisfactorily solvable by the conventionally used bearing and sliding techniques.

Often it is not practical to include such guide- and drive-means within the work chamber, where the drive shaft or the workpiece is expected to operate in extreme conditions - for example contaminant-free or evacuated environment, elevated working temperatures or corrosive atmosphere. Under such conditions the means are, themselves, a source of contaminants and corrosive products or they are not able to work sufficiently. In such cases the drive shaft has to extend from without into the chamber and the means for controlling the movements of the workpiece are arranged outside the chamber. Usually it has been the practice heretofore to employ dynamic sliding seals cooperable between the enclosure and the drive shaft.

Sealing a sliding shaft is a difficult task. One conventional method is to surround the shaft with a close-fitting sleeve and then fill the annular space between the shaft and the sleeve with a high density lubricant (Fig. 1).

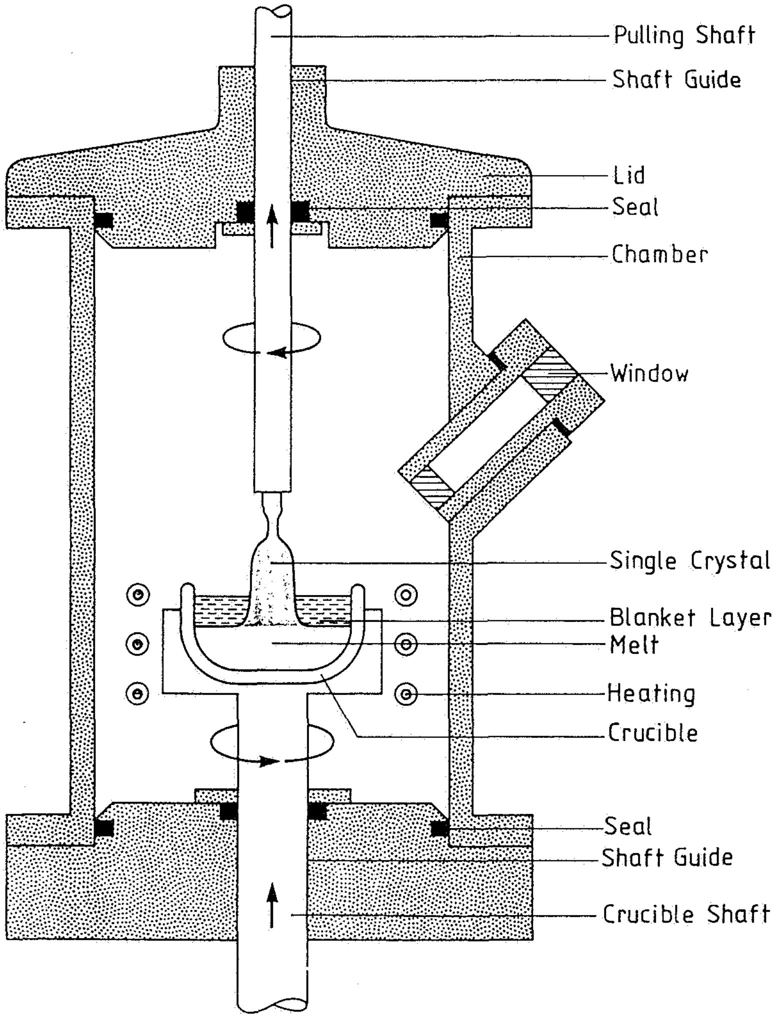

Fig. 1: Czochralski crystal growth apparatus

A modern improvement in sealing technology calls for the use of a magnetic fluid as lubricant working in conjunction with a magnetic shaft piece and a magnetically permeable sleeve or vice versa. This concept suffers from the problems of migration of the lubricant out of the annular space, limited working temperature and poor corrosion resistance. Furthermore seals are vulnerable to destructive action of deposits generated by the process, which find their way to the moving parts of the seals and have an abrasive or deteriorating effect thereon.

Vice versa, abrasion products generated by the residual friction effects in the seals may pollute and destroy the working process taking place inside the chamber.

The reliability of such seals is influenced adversely according to the degree to which atmospheric gas leaks past the seals into the enclosure or volatile process gas leaks out. These leakage effects depend on the problems summarized above. So the reliability of this mechanical solution is often less than satisfactory in the mentioned situations or applications.

Moreover, friction generated vibrations or scattering resulting from the mentioned frictional contact between shaft and sleeves may result and give rise to spontaneous defects of sensitive processes.

Because of the relatively stiff contact of the housing with the shaft, external influences on the apparatus in the form of vibrations or shocks also can not be prevented from detrimentally affecting processes.

Thus, also from the standpoint of vibration and shock isolation this solution is impractical in many situations as is described, by way of example, later on.

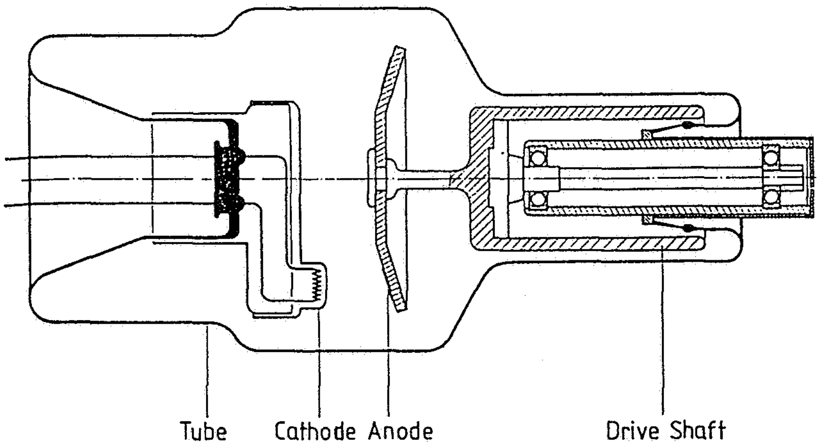

Fig. 2: Rotary anode X-ray tube

A more or less sufficient conventional method provides only the driving means, like electric motor stators or magnetic coupling cages, outside the chamber and arranges the shaft including the bearing unit within this enclosure. Thus, the chamber may be hermetically closed. In vacuum applications, as shown in Fig. 2, special non-lubricated ball bearings have to be used. Appropriate bearings for heated and/or corrosive environments are not commonly available.

The bearing wear increases with the square of rotary speed. It is not possible to avoid bearing noises, which increase with rotary speed. At high rotational speed applications these effects are a main disadvantage, particulary in medical work, as demonstrated later on.

For this area, classical systems using conventioanl ball bearings are not well fitted. To overcome the mentioned problems, modern magnetic bearing technology may be used. This paper presents a wide gap permanent magnet biased magnetic bearing system. Its performance is demonstrated by example of two significant applications.

2. PERMANENT MAGNET BIASED MAGNETIC BEARING

The basic configuration of the magnetic bearing system used in the applications mentioned above was designed in the late 60's. It is described in more detail in previous papers [1,2].
Figure 3 shows the basic system using a non-laminated rotor collar made of ferromagnetic mild steel and an annular stator magnet made e.g. of bariumferrite-material. The axially magnetized permanent magnet surrounds the collar, thus forming an annular ring-shaped gap between the collar and the magnet.

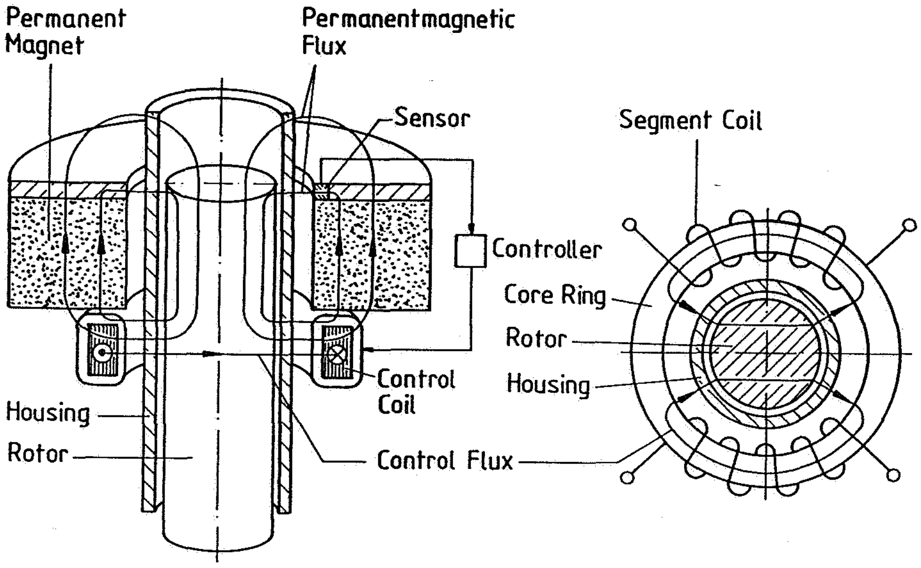

Fig. 3: Wide gap, permanent magnet biased magnetic bearing system

Along the axial direction, the rotor shaft is stably suspended within the region of maximum field energy density of the permanent magnet. The stiffness of this magnetic spring may be influenced by an additional active stabilization (not shown). This means can also be used to enhance the low structural damping. But in many applications the passive stabilization of the axial collar position results in suffient conditions.

In the radial directions an equilibrium position exists for the collar at the symmetry axis of the ring magnet. But this equilibrium is unstable and therefore a conversion of the unstable equilibrium in a stable one is required. It means that active stabilization of the collar position in two orthogonal radial axes is necessary.

The active stabilizing device comprises contactless position sensors, electronic control means and electromagnetic actuators.
In this bearing system magnetoresistive field plates can be used for pick-up of the radial collar or shaft position. This allows for the accommodation of a metallic tube between rotor shaft and the stator package, which would not be possible by using optical or high-frequency actuated pick-up means. The biasing field required for proper operation of these sensors is supplied by the permanent magnet. The thermal sensitivity of the magnetoresistive pick-up system does not introduce any drift problems of the shaft position, due to an automatic zero power control circuit incorporated in the stabilization electronics. So the radial collar position is merely determined by the permanent configuration and the static radial load exerted to the shaft.

Two pairs of actuator coils wound on a common laminated ferromagnetic ring shaped core are arranged immediately next to the permanent magnet. The permanent magnetic flux passes through the lower gap in parallel to the control flux. Thus the control flux modulates the normally symmetric permanent biasing flux in an antisymmetric manner, hence producing controllable radial forces. The radial magnetic forces exerted to the shaft are proportional to the product of Bo and ΔB, where Bo represents the biasing induction and ΔB the differential amplitude of the control induction generated by the control coils in radial direction.

Besides the conversion of the radial instability into a stable one, the biasing effect provides the desirable benefits of

- linearizing the force versus current relationship
- multiplying the effectiveness of the control ampereturns
- zero force at zero current in the passive equilibrium position, which consequently may represent the reference axis for the position control circuit
- minimizing of electric power consumption
- feasibility of large radial gaps between rotor and stator

Therefore, the electronic control device may have a relatively simple structure because it is freed from linearization networks for either sensor and force signals and needs only small power consumption. So it can be flexible adapted to the application requirements.

The mentioned applications mainly derive benefit from the following facts:

- All radial as well as axial forces exerted to the shaft are transmitted from the stator to the shaft via radial gaps
- Relatively large radial gaps can be provided between the rotor and stator elements which are magnetically excited by no electric power consuming permanent magnets - the volume and material of these stator magnets can be easily adapted to the required magnetic energy in the gaps.
- The bearing concept allows for the accommodation of compact tubes in the gap, as a hermetic seal between the working environment of the shaft and the outer atmosphere - neither windows nor feedthroughs are necessary
- The arrangement of thick-walled tubes of non-magnetic stainless steel and/or heating, insulating and cooling elements in the annular gap is possible.
- The only bearing components attached to the shaft are non laminated ferromagnetic steel collars or cylinders - a variety of materials ranging from mild steel to ferromagnetic stainless steel has been realized and used.
- The use of iron-cobalt alloys gives the chance to set out the shaft to elevated working temperatures - materials with a Curie-temperature up to 950°C are available
- Linear motion of the shaft along the tube axis without geometrical limitation by bearing or drive components is accomplished
- Very low transmissibility of shocks and vibrations from the environment is achieved - the magnetic bearing acts as an vibration isolator

Thus the mentioned magnetic bearing concept covers a lot of the complex requirements imposed by modern technical applications.

3. APPLICATIONS OF THE MAGNETIC BEARING SYSTEMS

3.1 Rotary anode X-ray tube

3.1.1 State of the art

Rotary anode X-ray tubes for medical diagnostics are designed such that its anode is rotated at high speed in a highly evacuated seal glass envelope (Fig. 2). The anode emits X-rays as it is bombarded by high speed electrons emitted from a cathode. Unfortunately, the electron beam energy is mostly converted into heat. Thus, the anode is heated up to elevated temperatures depending on the electron energy and the exposure time. In order to keep the anode temperature in a limited range the energy is spread over the circumference of the rotating anode. That means the exposure time has to be in correlation with the revolution time of the anode.

This type of X-ray tube is cooled only by giving off heat radiation to the surrounding environment. The application range of these tubes extends besides operation for fluoroscopy, for which the rotary anode tube must posses a high permanent load-carrying capacity, to operation at high power flash and spot density with exposure times in the range of a few milliseconds. Such short time exposures are applied in medical diagnosis, for example in taking x-ray pictures of an organ in a living body. In such cases the rotary anode has to run at full rotation speed only during the short flash for taking the picture.

As the rotational revolution time is matching the exposure time the flash energy is uniformly distributed at the anode rim. For example, at a desired exposure time of 3 milliseconds the suitable rotational anode frequency should be in the range of 300 RPS.

In the case of conventional tubes this frequency is limited to typically 150 RPS in view of life time, temperature, noise and power restrictions caused by the up to now used ball bearings. Due to the wear of these bearings, which causes the most serious lifetime limit of the tube, it is not possible to let the anode continously turn longer than is necessary. Therefore, the tube is not ready for photographing at any time: It has to be accelerated from still stand to the working frequency before and breaked to stillstand after each flash. Powerful drive units with a power of several Kilowatts have to be installed to keep the acceleration and breaking time as short as possible in order, on the one hand, to keep the waiting time of the operator as short as possible, and, on the other hand, to diminish the bearing wear, which increases, as mentioned above, with the square of the bearing speed. A further disadvantage is that this drive and bearing means are the source of unwanted noises which increase with the rotating frequency and with the drive power. This sound emission is bound to be disturbing, particularly in the field of human medicine.

3.1.2 Advanced design

To overcome the above mentioned problems an improved rotary X-ray tube of the type generally described above has been developed in our laboratoy in collaboration with Siemens AG, Erlangen [3]. In this machine a contactless and therefore wearing free support of the drive shaft of the anode is provided and the anode current is supplied via a touching contact which is designed as a magnetic switch.

Figure 4 shows a longitudinal section of this embodiment. The disc shaped anode is located inside the glass housing opposite to the cathode. It is fixed on the closed end of the drive shaft which has the form of a hollow cylinder. The shaft consists of a series of collars fixed to each other coaxially to the shaft axis. The bearing collars in the area of the magnetic bearings are made of ferromagnetic mild steel while the connecting collar consists of non magnetic steel. At the open end of the shaft a drive collar made of copper is affixed to the shaft. The shaft parts are connected by welding or soldering methods in order to prevent slits and holes which may be the source of outgassing effects and resulting vacuum contamination. The bearing and drive package is arranged outside of the envelope. Two magnetic bearing stators of the type described and the drive stator are coaxially fixed in this stator package.

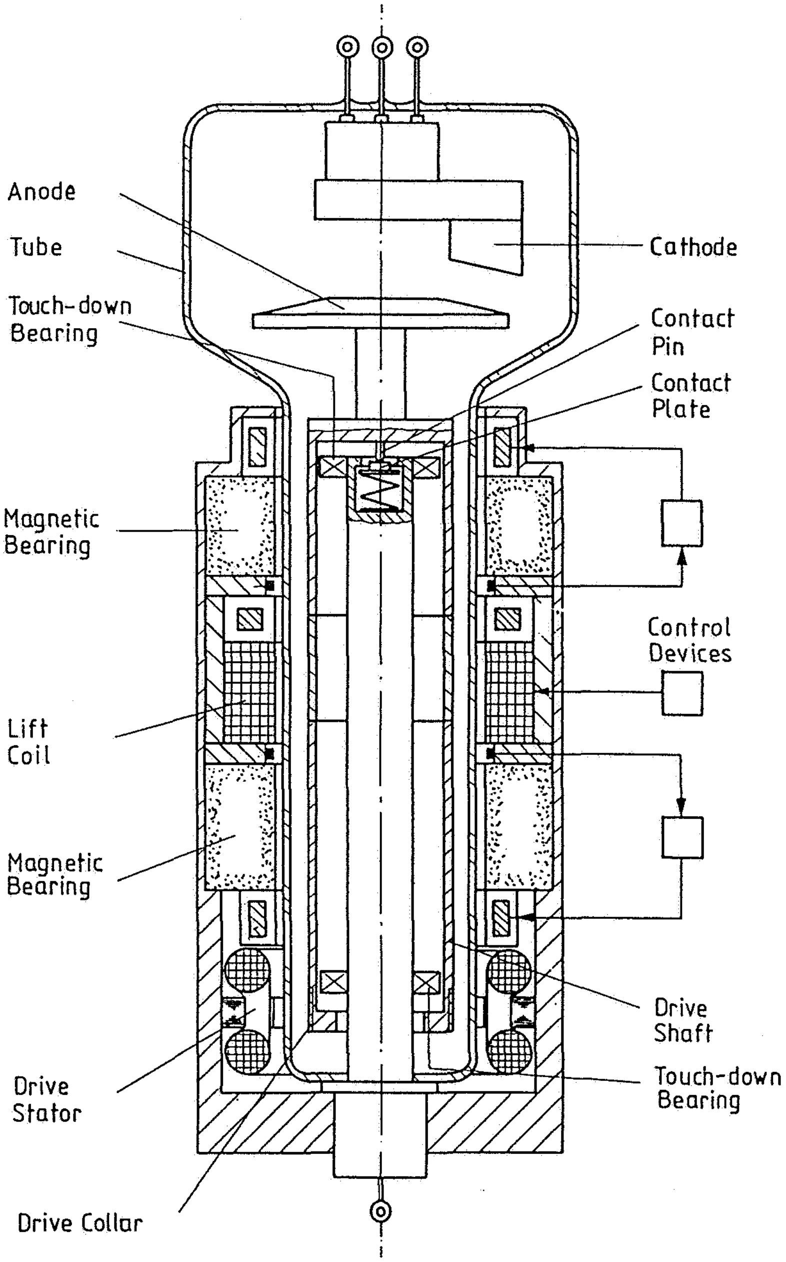

Fig. 4: Rotary anode X-ray tube with magnetically supported anode

An additional electromagnetic coil is provided in the space between the bearing stators. The wire of this coil is wound in the circumferrential direction. Thus the current generated magnetic field of this coil causes an axial force exerted to the shaft which causes an axial motion of the shaft. The resulting shift direction corresponds to the current direction, the shift amplitude to the current amplitude. Hence also with this rotary anode design it is possible to set or adjust the rotary anode at different working positions by external control of the coil current. The procedure can be used to open and close the axial touching contact for current supply to the anode.

This contact, for example, consists of a pin coaxially affixed to the drive shaft and a spring mounted contact plate at the stationary axis. The axis is surrounded by the hollow shaft and carries the anode voltage. Thus the anode current is fed from outside the tube via the axle to the anode. The construction allows opening and closing of the slip contact in the anode voltage circuit by moving the anode to open and close position while the drive shaft is kept in continuous rotation. In the consequence this X-ray tube is in practice ready for operation without loss of time under condition of minimum wear, because wear happens only at very short slip contact time.

Two lubricant-free touch-down bearings are fixed to the axle. Due to a given radial and axial clearance they only come into action in the event of bearing breakdown or switch off. Thus, such a construction provides reliable operation because by accident the shaft is caught approximately in position by the axle.

A wide radial gap is provided between the drive shaft and the stator elements in order to insulate the shaft electrically from the housing tube. Also the stationary axle is connected to the stator unit via electrically insulating materials. A gap width of 13 mm enables the anode to operate at voltages up to 100 KV positive with respect to ground. Therefore a significant increase of the electron voltage by the factor 2 up to 200 KV may be achieved only by using conventional 100 KV voltage supply equipment.

The concept described has been realized and tested in 1979. (Fig. 4,5)

The significant test results are the following:

- Working speed: 300 RPS
- Drive power: A few watts at working speed
- Anode-cathode-voltage: 150 KV, symmetric to ground
- Shaft-temperature: 600°C
- Stator-temperature: 120°C

This machine was the first known rotary anode x-ray tube provided with contactless magnetic bearings. The unique features of this concept are confirmed by test:

- Continous anode rotation resulting in steady state operation
- Increase of effiency due to the realisation of
    - increased speed rotation of the anode
    - increased electron voltage
    - low drive power consumption
- Easy installation
- Quiet operation due to low power motor and the absence of noise generating rolling bearings and friction effects

By using the described contactless magnetic bearing concept the effectiveness, the handling procedure, the load capacity and the compatibility with the environment of rotary anode X-ray tubes are significantly improved.

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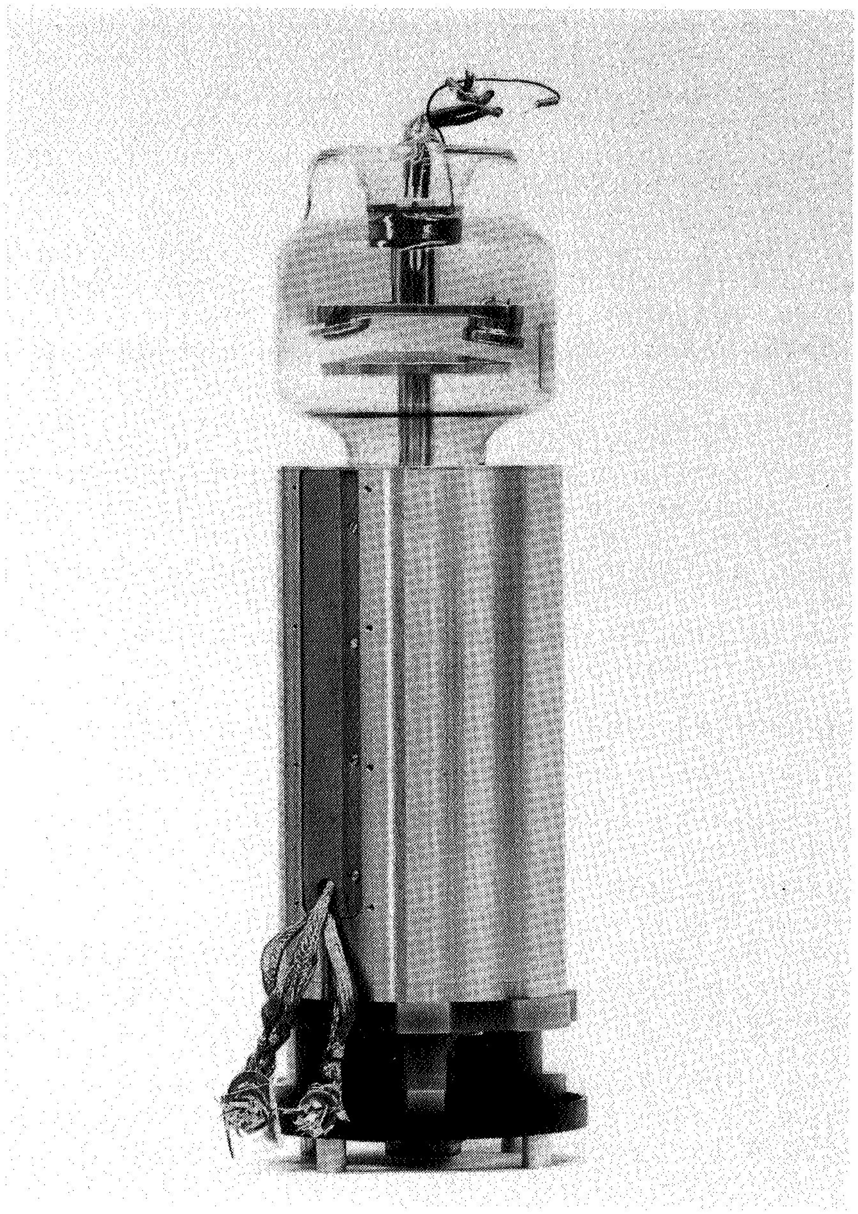

Fig. 5: Rotary anode X-ray tube with magnetically supported anode

3.2 Apparatus for growing semiconductor crystals from the melt

3.2.1 State of the art

3.2.1.1 Czochralski-Method

Similar complex bearing and sealing condition are required in the fabrication area of high quality semiconducting crystals.

Such crystals are typically formed using the Czochralski crucible melt method (Fig. 1) [4] in which single crystals are pulled from a melt which is contained in a crucible. The necessary pull motion is usually achieved by axially moving and rotating of both the melt and the growing crystal by supporting shafts.

In order to ensure continuous growth of the crystal of utmost perfection, i.e. orderly crystal lattice structure, certain process and apparature requirements have to be fulfilled. In growing such crystals, it is an essential demand that the crystal-growing operation is conducted in a contaminant-free environment so that the crystals formed are of utmost purity. Therefore, the growing process has to be performed in a closed chamber to enable any desired atmosphere to be maintained in the working area. The number of seals, windows and feedthroughs has to be reduced as far as possible in order to minimize the risk of breakage, air leakage or toxical gas leaking out.

Dynamic seals of drive shafts are vulnerable to destructive action of deposits of the heated material or by chemically reactive process gas; so they may foul the drive shaft and its seal at the point of entry into the chamber.

Furthermore it is very important that both the crystal and the melt are moved extremely smoothly and in a very controlled manner to ensure continuous growth of the crystal with an orderly lattice structure. Slightest discontinuities of the shaft velocity as caused by vibrations, shocks and unbalances may introduce unstable, disturbing effects into the solidification front, which result in dislocations in the final crystal structure.

As mentioned above, either the commonly used seals themselves, as well as the driving and supporting means of the shaft are a source of the undesired effects. These elements need essential refinements in order to achieve a sufficiently controlled motion of the shaft.

Furthermore, it is necessary to control the size of the growing crystal body in order to keep the cylindrical part used for electronic device production within tight limits. Usually direct video measurement of the crystal diameter via an observation window supports closed-loop automatic diameter control. Another diameter monitoring method currently used is based on controlling the rate of the crystal weight gain. The control is realized by means of closed-loop adjustment of the shaft lift rate and/or melt temperature.

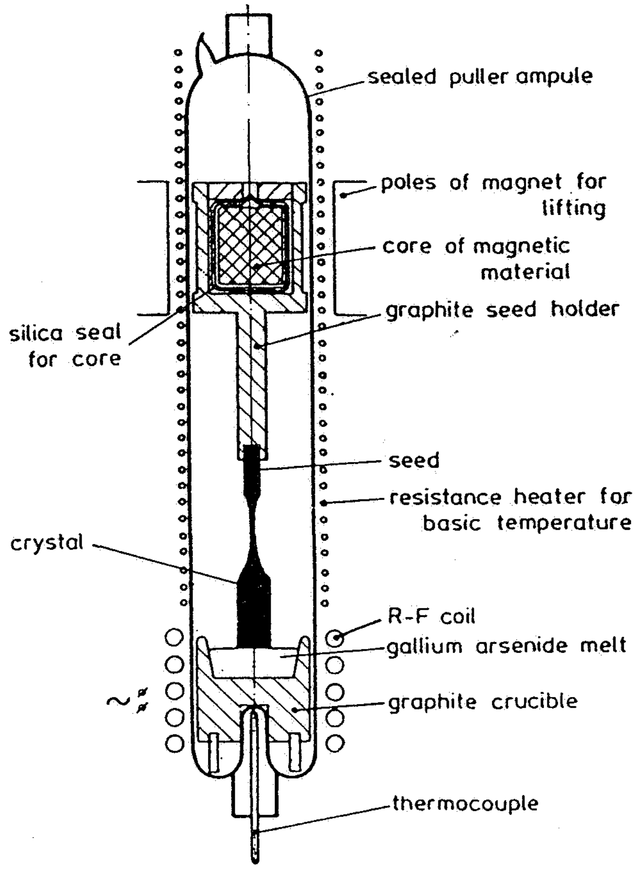

Fig. 6: Gremmelmaier crystal growth apparatus

The growth of compound semiconductor crystals as for example galliumarsenide creates many more processing problems than single element crystals like silicon. It is the main demand that the ratio of the compound elements gallium and arsenic has to be kept precisely stable during the growing process. Unfortunately, arsenic is very volatile at the melting point of GaAs, so that it tends to evaporate from the melt. Consequently, the stoichiometry of the melt and the growing crystal is disturbed.

Up to now two methods are used to avoid these disturbations:

3.2.1.2 Liquid-Encapsulated Czochralski-Method

In the so called LEC (Liquid-Encapsulated-Czochralski)-process a blanket layer of molten boron oxide is floated on top of the melt as to prevent the mentioned evaporation.

Unfortunately this LEC-layer is responsible for a relatively high dislocation density. Plastic crystal deformation is caused by the high temperature gradient on the crystal surface when pushed through the layer surface. Currently no LEC-apparatus is known which maintains the temperature gradient in a sufficiently narrow range.

3.2.1.3 Gremmelmaier-Method

The so called HWC (Hot-Wall Czochralski)-process [5]as shown in Figure 6 provides heating of the process chamber to a temperature above the sublimation and condensation point of arsenic (~ 600°C). So an arsenic ambient is created inside the chamber. The transport of arsenic out of the melt is prevented and the stoichiometry is not lost. The chamber is completely sealed by a puller ampule. The crystal support shaft is magnetically coupled to drive means, which are arranged outside the chamber and are moved while radially sliding at the chamber inner wall surface. Due to the friction induced problems of vibration and wear the operation control is very difficult and the load capability is limited to several hundred grams, so this method has not succeeded for application at an industrial scale.

Also the diameter control of the described growth methods for GaAs is much more difficult than with silicon. Either the blanket encapsulation layer or the sliding coupling means prevent a sufficiently precise control of the diameter of the growing crystal.

3.2.2 Advanced design

An embodiment of an improved apparatus suitable for the growth of crystal according to the mentioned aspects will now be described with reference to Figure 7. This drawing is a vertical sectional view of an Hot-Wall-Czochralski-apparatus for the growth of GaAs crystals from the melt utilizing the magnetic bearing technique presented above [6,7].

Both crystal and crucible are carried and transported by shafts which are magnetically suspended by the surrounding stator means. These stator means and the annular drive stator are assembled to a compact stator package similar to the X-ray tube embodiment described.

The stators are mechanically connected to linear drive means which effect the axial motion of crystal and crucible. The rotary motion is accomplished by rotary drive stators.

The bearing means are designed to provide a load capability of more than 20 kg at a gap width of 26 mm. This gap allows for the accommodation of hermetically sealed tubes made of Quartz and additional heating, insulating and ccoling means. The inner surface of the tube can be heated up to 800°C while the outer surface of the tube unit can be maintained near room temperature. Thus overheating of the stator unit is prevented.

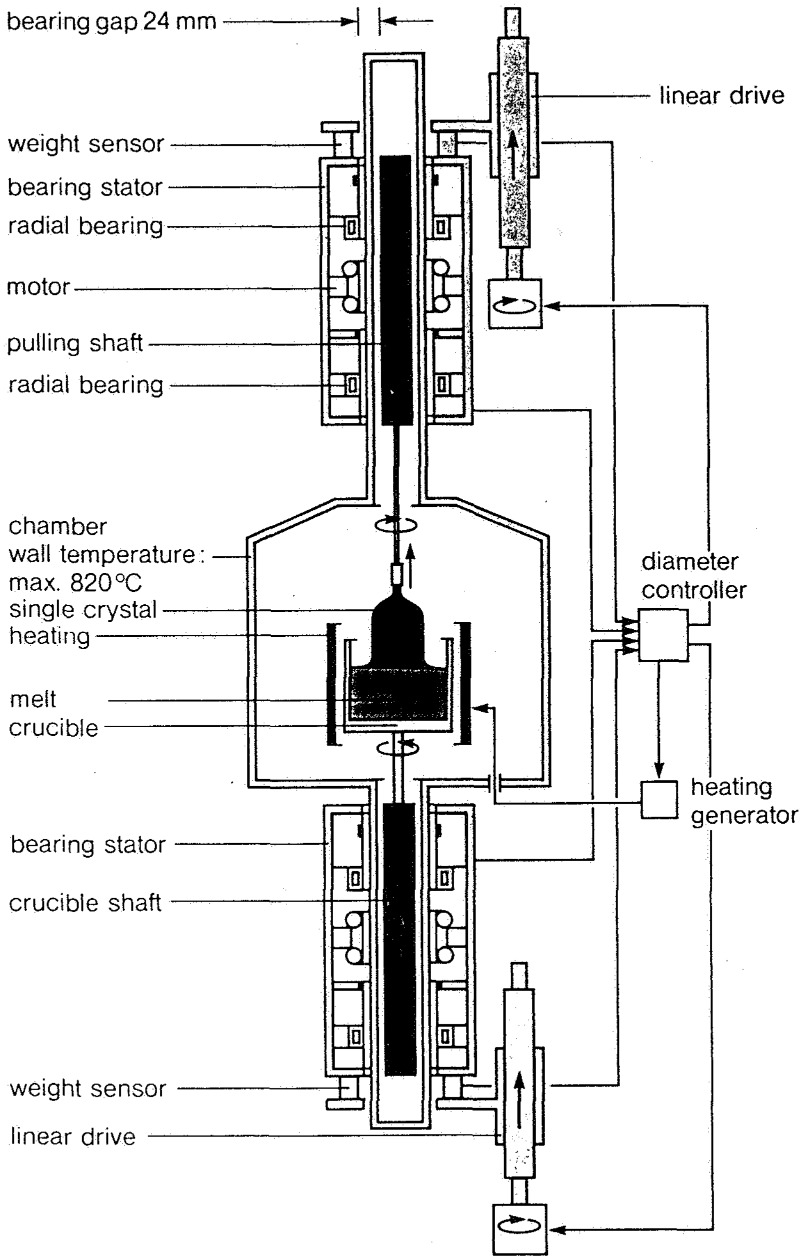

Fig. 7: Hot-wall Czochralski crystal growth apparatus with magnetically suspended pulling and crucible shaft

The bearing collars, which are fixed to the shaft in a similar manner as shown with the X-ray tube, are made of an iron-cobalt alloy with a Curie-temperature of 950°C. The entire shaft including the motor means is hermetically cladded by a corrosion-resistant quartz tube.

Consequently, this machine fullfills the basic requirements of the HWC-method for the growth of GaAs monocrystals at an industrial scale.

Beyond it this concept further provides two different simultaneously usable methods for monitoring the diameter of the growing crystal[8]:

(1) Force transducers are provided between the stator unit and the linear drive means measuring the weight of the entire moving parts. The rate of crystal and melt weight gain derived from the force signal enables the method for a diameter control. The complete measuring unit is arranged outside the growth chamber. Consequently, this detection procedure is effected in a completely frictionless manner, and is also free from signal disturbing effects such as corrosion, pressure or temperature.

(2) In the second method, the drive energy consumed by the viscous friction between crystal and melt is detected. This depends mainly on the radius of the growing crystal and on the rotational frequency. The preferred application comprises

- the rotary drive unit, in this case, designed as an asynchronous motor
- sensor means for detecting the rotational frequency of the shafts and
- a control device for keeping the crystal or crucible in constant rotation.

Under such conditions, the drive currents or voltages only depend on the crystal diameter and consequently can be used as actuating signals in a closed-loop diameter control unit as mentioned above. Also in this embodiment no window or feedthrough is necessary.

In summary, the machine provides a contactless and wearless suspension of the crucible and the crystal carrying shafts in a hermetically sealed process chamber. The concept reduces to a minimum the number of static and dynamic seals, feedthroughs and windows, eliminates any source of friction and wear inside the growing chamber, provides high-precision monitoring systems for process automation, permits corrosive process atmosphere at elevated process temperatures, performs effective vibration and shock isolation.

Consequently, this machine permits us to make use of the Hot-Wall-Crzochalski-method for the growth of GaAs crystals of excellent purity and perfection at an industrial scale.

In cooperation with the competent German company Leybold AG, Alzenau, this concept has been succesfully tested (Figure 8). Several crystals with weights up to several kg have been grown under hot-wall conditions, i.e. the shaft had been heated up to 820^{o}C. A prototype of the machine for industrial fabrication of crystals has been built up and is just going under final test.

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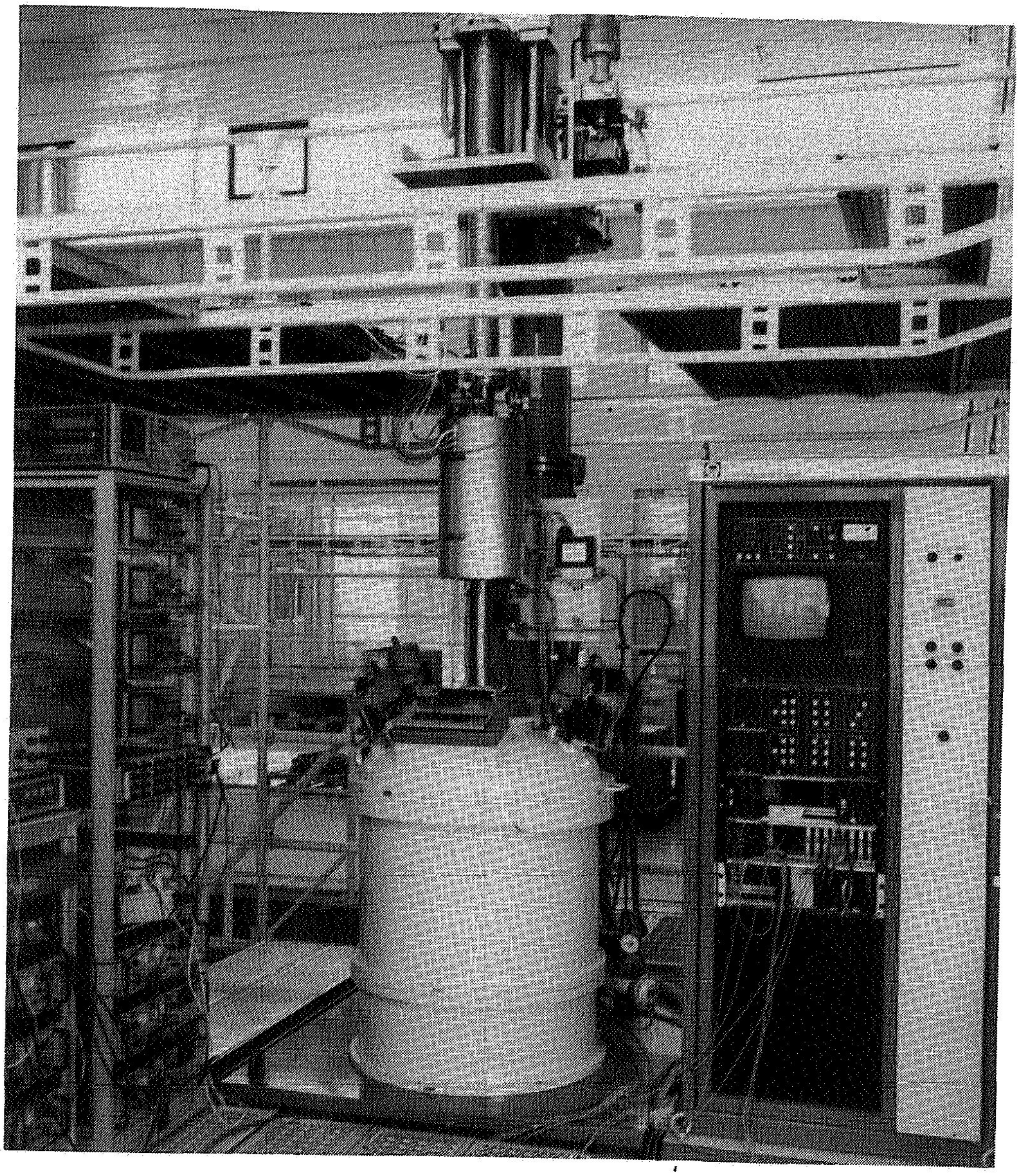

Fig. 8: Test set-up at Leybold AG, Alzenau

4. CONCLUSION

A practical permanent magnet biased magnetic bearing system is presented which permits relatively large gaps between stator and shaft (Fig. 9).

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Fig. 9: View into the bearing gap (24 mm)

It works very effectively, yet the bearing parts are very simple and inexpensive. For example, flat annular radio loudspeaker magnets, made of cheap Bariumferrite-material, simple coils and sensor systems and mild steel collars make up the entire parts of stator and shaft.

This bearing covers a lot of particular application requirements, as for example

- simplicity of rotor design
- low power consumption
- high and low rotor speed
- elevated process temperatures
- corrosive or ultra-clean process environment
- convenient assembling

Due to these advantageous particularities the concept may solve restricting problems of many modern technical systems affected to conventional guide technique thus enhancing their capacity to perform a task. As demonstrated by way of example two pretenting applications meet their technical liability free from the drawbacks of classical bearing, sealing and supporting means: A magnetically suspended rotary anode for medical X-ray tubes has been developed, which has been satisfactoraly tested. An apparatus for growing GaAs-crystals from the melt using the Hot-Wall-Crzochalski-techniques has been provided with magnetically suspended drive shafts and improved automatic process control devices. This machine allows for the production of GaAs monocrystals of improved quality and purity.

The applications exemplified derive their benefit essentially from the fact that large gaps can be realized between stator and rotor elements by using the magnetic bearing system described. As a consequence, this bearing concept enables us to overcome the restricting features of the conventionally used guiding and sealing technique for drive shafts and renders possible new advantageous design for a growing number of complex applications.

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