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SUPERCONDUCTING THIN FILM THERMOMETERS FOR CALORIMETRIC PARTICLE DETECTORS

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Abstract

At the Max-Planck-Institut and the Technical University of Munich we are developing thin film thermometers for calorimetric particle detectors with applications in elementary particle physics. We use superconductors operated at their transition from the normal to the superconducting state. In this region a temperature change results in a change in resistance, which is measured. We are trying to produce tungsten thermometers (α-structure) which should have a critical temperature of 15 mK. In order to avoid a contribution of β-tungsten, which has a critical temperature of several Kelvin, we grow α-tungsten epitaxially on $(1\bar{1}02)$ sapphire. The achievement of epitaxial growth is shown by X-ray diffraction. Up to now no superconductivity was observed in epitaxial films. We attribute this to the presence of an iron contamination, detected by SIMS, at the interface to the substrate. A polycrystalline α-tungsten film, which was evaporated at lower substrate temperatures without baking of the system, showed a superconducting transition at 15 mK.

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1 Introduction

At the Max-Planck-Institut für Physik and the Technische Universität München we are developing low temperature calorimeters for particle detection [1,2]. A calorimeter consists of an absorber in which the particle interaction takes place and a thermometer attached to the absorber. The basic idea of a calorimeter is to measure the temperature rise after the energy deposited by a particle interaction has thermalized and thermometer and absorber are in thermal equilibrium. The change in temperature ΔT due to an energy deposition E is given by

$$\Delta T = \frac{E}{C}$$

where C is the heat capacity of absorber plus thermometer. One has to keep the heat capacity C low in order to obtain large signals. Since the heat capacities of most materials decrease when one lowers their temperature, one can gain substantially in sensitivity by running a calorimeter at the lowest possible temperature. With a 19 g silicon absorber we presently achieve an energy resolution of 1 keV (FWHM) for the detection of single 60 keV photons.

The essential part of a calorimeter is the thermometer. We are using superconducting transition edge thermometers. A superconductor shows a strong temperature dependence of its electrical resistance in a narrow region around its transition temperature T_C. Within this transition region the resistance goes from the normal conducting value to zero in the superconducting state. A film made of a superconducting material can therefore be used as a thermometer. The operating temperature of the calorimeter is determined by the critical temperature T_C of the thermometer.

Developing thermometers that can operate at low temperatures in order to improve the sensitivity is one of the goals of the work done at the Max-Planck-Institute in Munich. The work reported on here uses tungsten which has a critical temperature of 15 mK.

2 Properties of Tungsten

Tungsten exists in three different phases:

The α-phase has a b.c.c. structure with a lattice constant of 3.165 Å. It occurs in pure bulk material and films. Its critical temperature for superconductivity T_C is 15 mK [3,4].

The β-phase has a A15 structure (lattice constant 5.083 Å) and a T_C of 3 to 4 K. This phase is stabilized by impurities and especially by oxygen [5]. It has been observed in bulk material and in films.

The γ-phase has a f.c.c. structure (lattice constant 4.12 to 4.21 Å), has only been observed in films, and shows a T_C of 4.6 K [6,7].

Since we want to operate our calorimeters at the lowest possible temperatures we are only interested in films of pure α-tungsten showing a T_C of about 15 mK. To our knowledge such a low T_C has up to now not been observed in thin films.

Furthermore the critical temperature of superconductors is strongly affected by magnetic impurities. It has been observed that the T_C of a superconductor is reduced by 1 to 10 mK per ppm of magnetic impurities [8]. Therefore the superconductivity of α-tungsten can be suppressed by magnetic impurities at a level of some ppm.

3 Production of Films

The films were produced in a UHV system by electron-beam evaporation. The system has a volume of 300 l and is fully bakeable. With a turbomolecular pump (pumping speed 1100 l/s for nitrogen) and a liquid nitrogen cooled titanium sublimation pump (pumping speed 12000 l/s for hydrogen) a base pressure of 6×10^{-12} mbar is reached. The substrate temperature can be controlled in a range from 300 °C to 1100 °C. Substrate holder and electron-beam evaporator are surrounded by liquid nitrogen cooled radiation shields. The pressure during the evaporation process is lower than 5×10^{-9} mbar. The films were prepared by evaporating a tungsten single crystal with a nominal purity of 99.999%.

There are three demands on the substrate material:

- Used as an absorber material it must have a low specific heat capacity.

- To avoid interdiffusion between thermometer and substrate its melting temperature has to be high.
- To suppress the growth of β or γ-tungsten the substrate should be oriented in a way that favours the epitaxial growth of α-tungsten.

We therefore decided to use sapphire as substrate material and to deposit the films onto the $(1\bar{1}02)$ plane [9,10]. Several films were produced at different substrate temperatures ranging from 800 °C to 1100 °C, with thicknesses between 2500 Åand 6000 Å.

4 Crystalline Structure

Structural analysis was performed with a Bragg-Brentano X-ray diffractometer. All $\Theta - 2\Theta$-scans showed only the reflections of the (002) plane of α-tungsten (fig. 1) with a measured mean lattice constant of (3.173 Å). Except for reflections of the $(1\bar{1}02)$ and the $(2\bar{2}04)$ plane of sapphire no other reflections were observed (fig. 2). This method detects only reflections of planes parallel to the surface of the substrate. The observed pattern can in principle be produced by crystallites of α-tungsten, which have all the (002) plane in parallel to the substrate surface but are randomly oriented relative to an axis perpendicular to (002) plane. To check for this, the sample was mounted in an orientation that showed a reflection of the (202) plane. Then measurements were performed while rotating it by an angle ϕ around an axis perpendicular to the (002) plane (fig. 3). From the fact that only four sharp reflections can be seen one can conclude that all crystallites are oriented in the same way. We also observed a small misorientation of about 3° between the (002)-W-plane and the substrate surface, which is in good agreement with the predicted value of 2.8° for epitaxial growth of tungsten on this plane [11].

At poor vacuum conditions (p=5×10^{-6} mbar) and low substrate temperatures we observed the growth of polycrystalline α-tungsten (fig. 4).

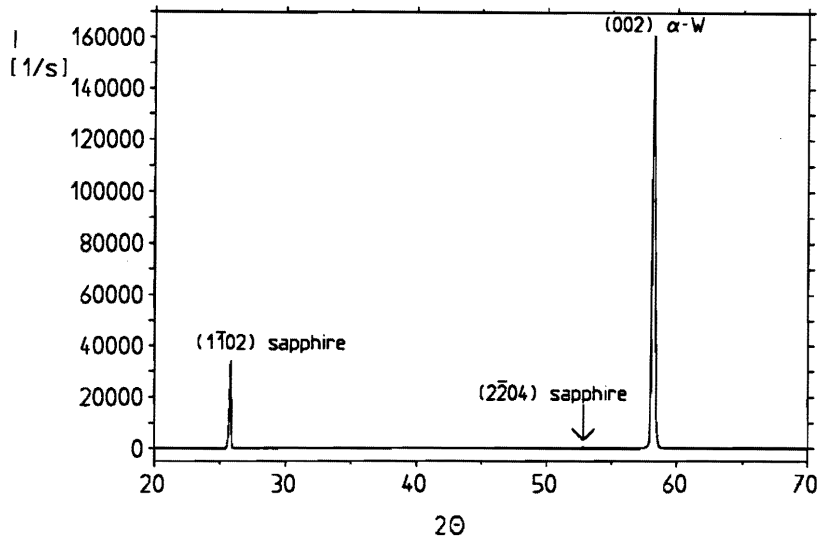

Figure 1: $\Theta - 2\Theta$-*scan of a tungsten film grown on* $(1\bar{1}02)$ *sapphire.*

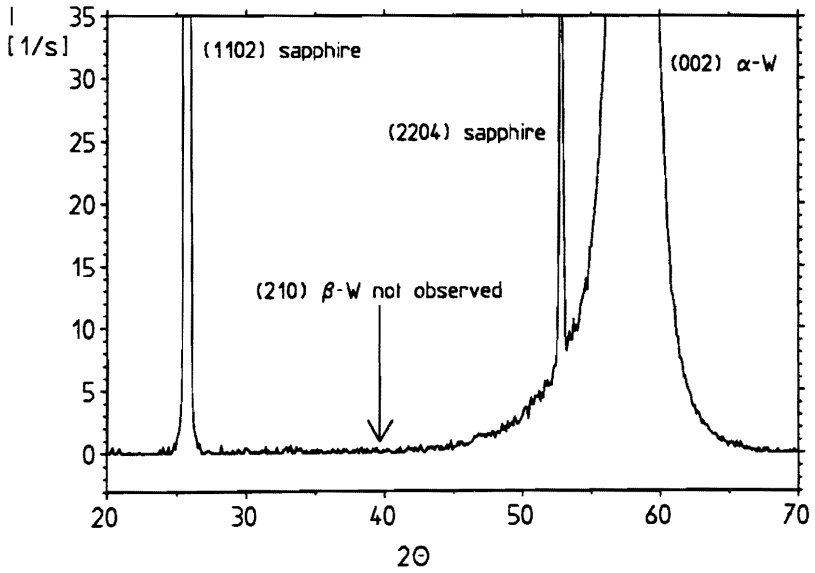

Figure 2: *Enlarged section of fig. 1. No reflections of polycrystalline* α, β *or* γ*-tungsten are observed.*

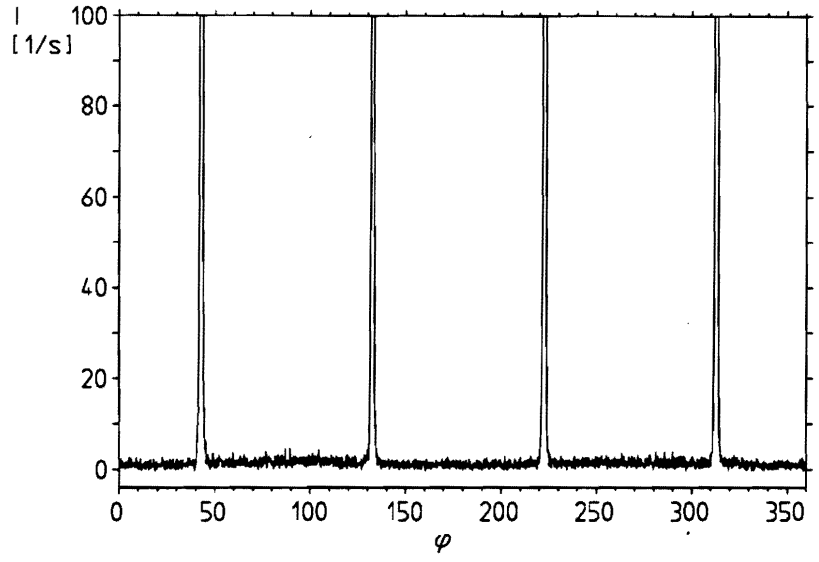

Figure 3: *ϕ-scan of [202] α-tungsten on sapphire (same film as in fig. 1)*

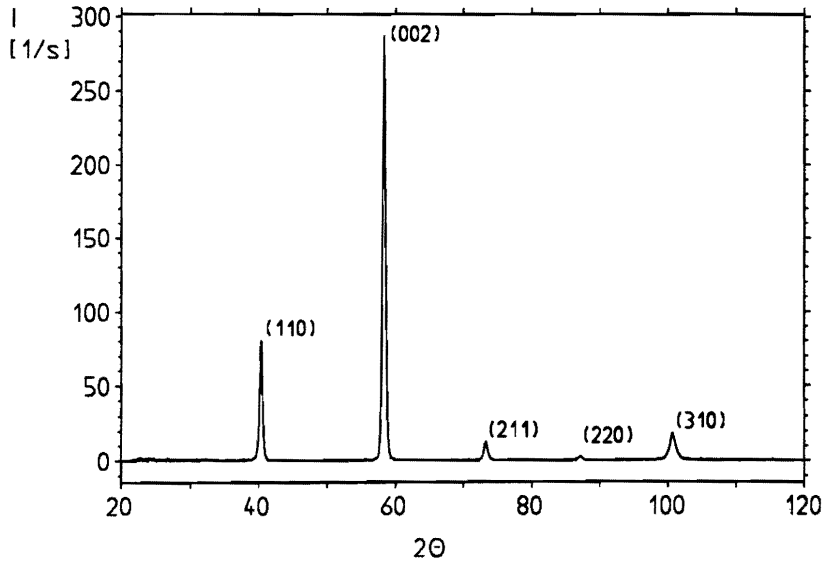

Figure 4: *$\Theta - 2\Theta$-scan of a polycrystalline α-tungsten film grown on $(1\bar{1}02)$ sapphire.*

5 Superconducting Properties

None of the epitaxial films showed superconductivity down to a temperature of 9 mK, while the evaporation material had a measured T_C of about 15 mK. We therefore performed a SIMS analysis of the films and the evaporation material. The iron contamination of the evaporation material was on the order of 0.1 ppm. The purity of the films was comparable to the evaporation material except for a region near the substrate which contained about 1000 ppm of iron. It is likely that this layer suppresses the superconductivity of the whole film. The source of this contamination is probably the stainless steel screws in the substrate holder, which we intend to replace by vanadium screws.

Very recently we observed superconductivity in the polycristalline tungsten film (fig. 5). The transition of this film is quite broad and occurs in

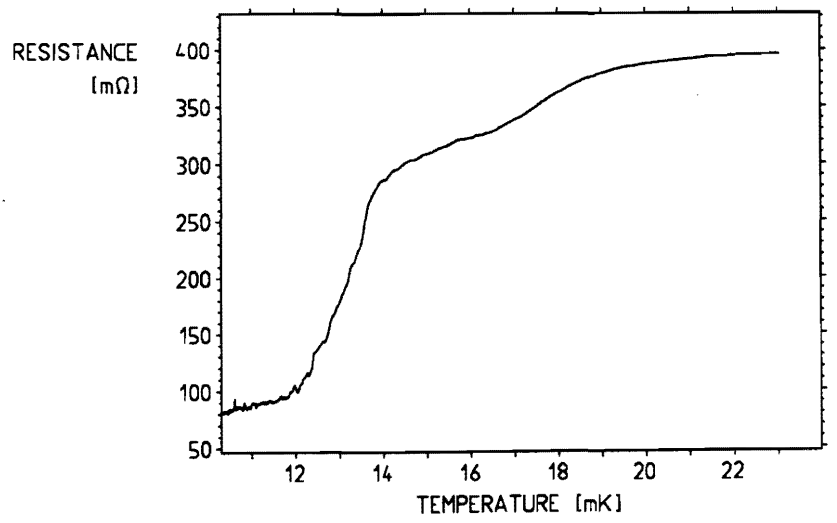

Figure 5: *Superconducting transition of a polycrystalline α-tungsten film (same film as in fig.4).*

a temperature region around 15 mK. Producing this film the substrate was not baked out and the film was evaporated at a relatively low substrate tem-

perature (500 °C). Therefore it probably contains less magnetic impurities. A SIMS analysis will be performed.

6 Conclusions

We produced a polycrystalline α-tungsten film which shows a superconducting transition at 15 mK consistent with the measured value of the bulk material. We also produced epitaxial α-tungsten films on sapphire, which did not show superconductivity. We attribute this to an iron contamination at the interface to the substrate. Solving this problem we hope to produce epitaxial tungsten films showing a sharp transition to superconductivity at 15 mK. Such films could be used as extremely sensitive thermometers for low temperature particle detectors.

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