A new molecular beam epitaxy system for the growth of heavy fermion thin films

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Introduction

$YbRh_2Si_2$ is a prototypal compound of this type of materials exhibiting a Kondo destruction quantum critical point as its antiferromagnetic phase is fully suppressed by the application of a small magnetic field [1]. From studies of the cubic compound $Ce_3Pd_{20}Si_6$ it is concluded that dimensionality is an efficient way to tune through the theoretically suggested [2] global phase diagram for antiferromagnetic heavy fermion compounds [3]. The successful molecular beam epitaxy (MBE) growth of single crystalline thin films of $YbRh_2Si_2$ would provide the unique ability to tune this material to the extreme 2-dimensional limit. Recent results on for $CeIn_3/LaIn_3$ [4] and $CeCoIn_5/YbCoIn_5$ [5] superlattices are encouraging and validate our approach.

We have set up an MBE system equipped with a standard evaporation cell for Yb and two electron beam evaporators for Rh and Si, and have succeeded to grow first $YbRh_2Si_2$ thin films on Ge.

Motivation

- Establish film thickness or superlattice period as quasi-continuous tuning parameter through the global phase diagram of heavy fermion compounds.

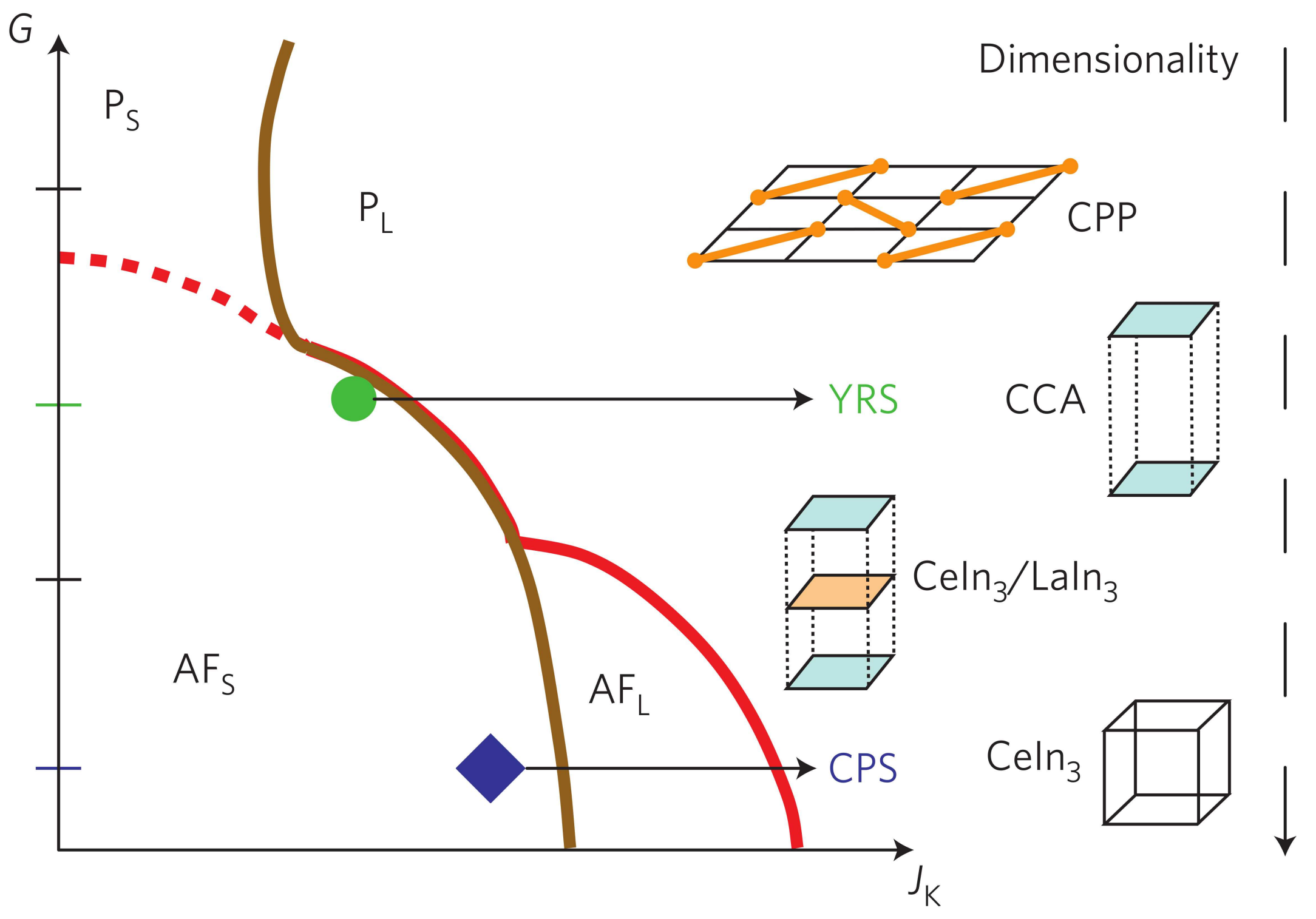

FIGURE 1: Global zero-temperature phase diagram of antiferromagnetic heavy fermion compounds [3]. The vertical axis represents the magnetic frustration parameter G, the horizontal axis the Kondo coupling constant J_K. The thick lines represent quantum critical points separating antiferromagnetic (AF) from paramagnetic (P) phases and phases with small (S) from phases with large (L) Fermi volume. The dimensionality of the compounds is connected to the magnetic frustration parameter G. The compounds are labeled as follows: YRS: $YbRh_2Si_2$, CPS: $Ce_3Pd_{20}Si_6$, CCA: $CeCu_{6-x}Au_x$, CPP: Ce_2Pt_2Pb.

- Perform microwave experiments to study charge and spin dynamics near the quantum critical point. Instead of coupling the investigated material to a superconducting resonator, it will be possible to manufacture resonators out of the heavy fermion compound itself and investigate the quality factor of these devices.

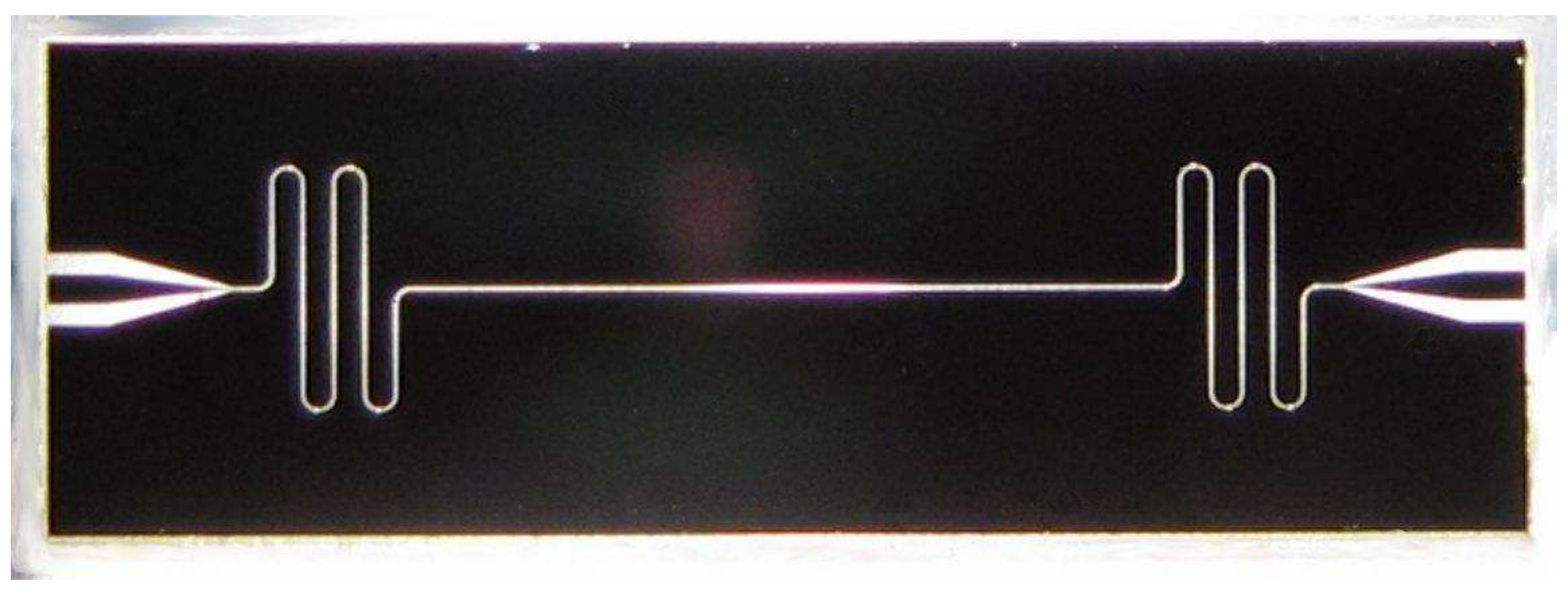

FIGURE 2: Resonator structure used in microwave experiments [6].

- Investigate the properties of molecular beam epitaxy grown heavy fermion compounds under positive and negative strain through lattice mismatching with respect to different substrates.

MBE setup

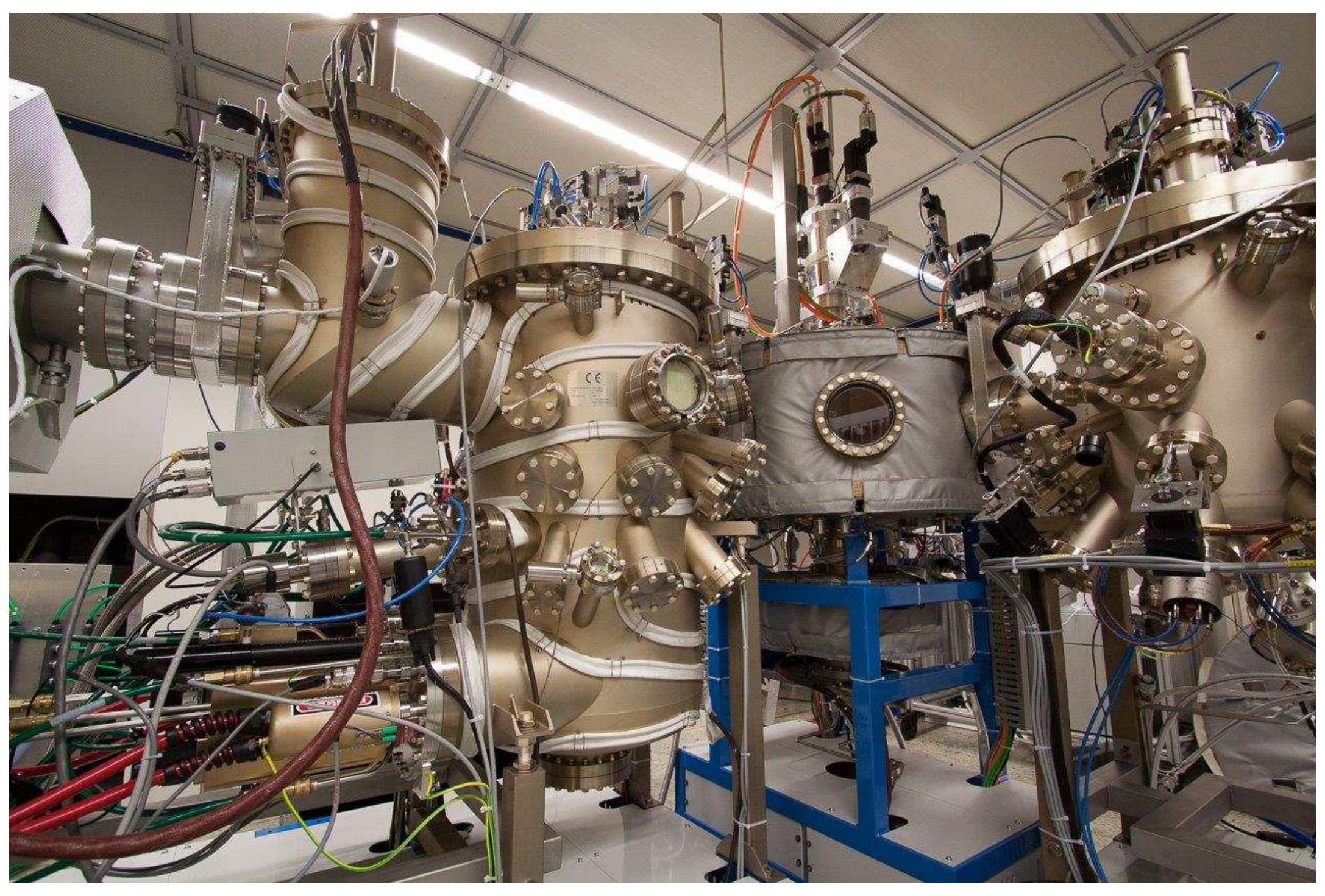

FIGURE 3: Photograph of the used MBE system (Compact21, Riber). It consists of two growth chambers, one for III-V semiconductors (right) and one for intermetallic compounds (left). In the center, there is a load and storage chamber.

Material

$YbRh_2Si_2$:

- Space group: I4/mmm
- Tetragonal $ThCr_2Si_2$-type structure
- Lattice parameters: a = 4.007 Å, c = 9.859 Å [7]

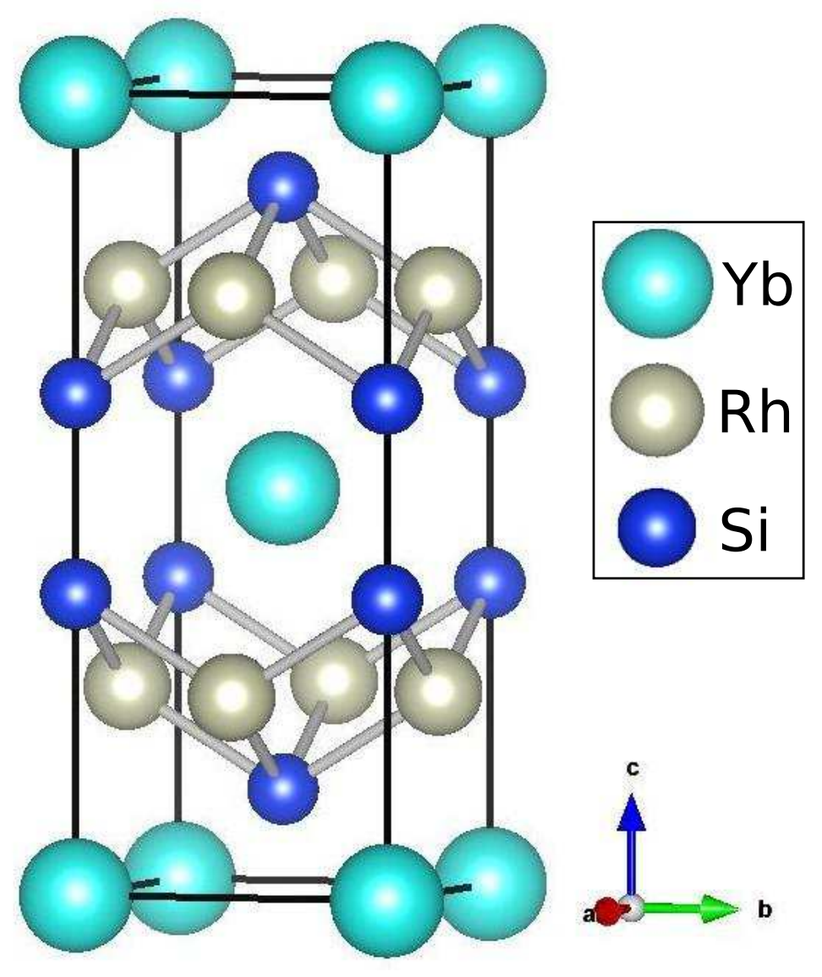

FIGURE 4: Unit cell of $YbRh_2Si_2$.

- $YbRh_2Si_2$ exhibits a quantum critical point at a magnetic field $B_c = 60\,\mathrm{mT}$ perpendicular to the c-axis, separating an antiferromagnetic phase below from a paramagnetic phase above B_c. T^* marks the energy scale associated with the Kondo destruction.

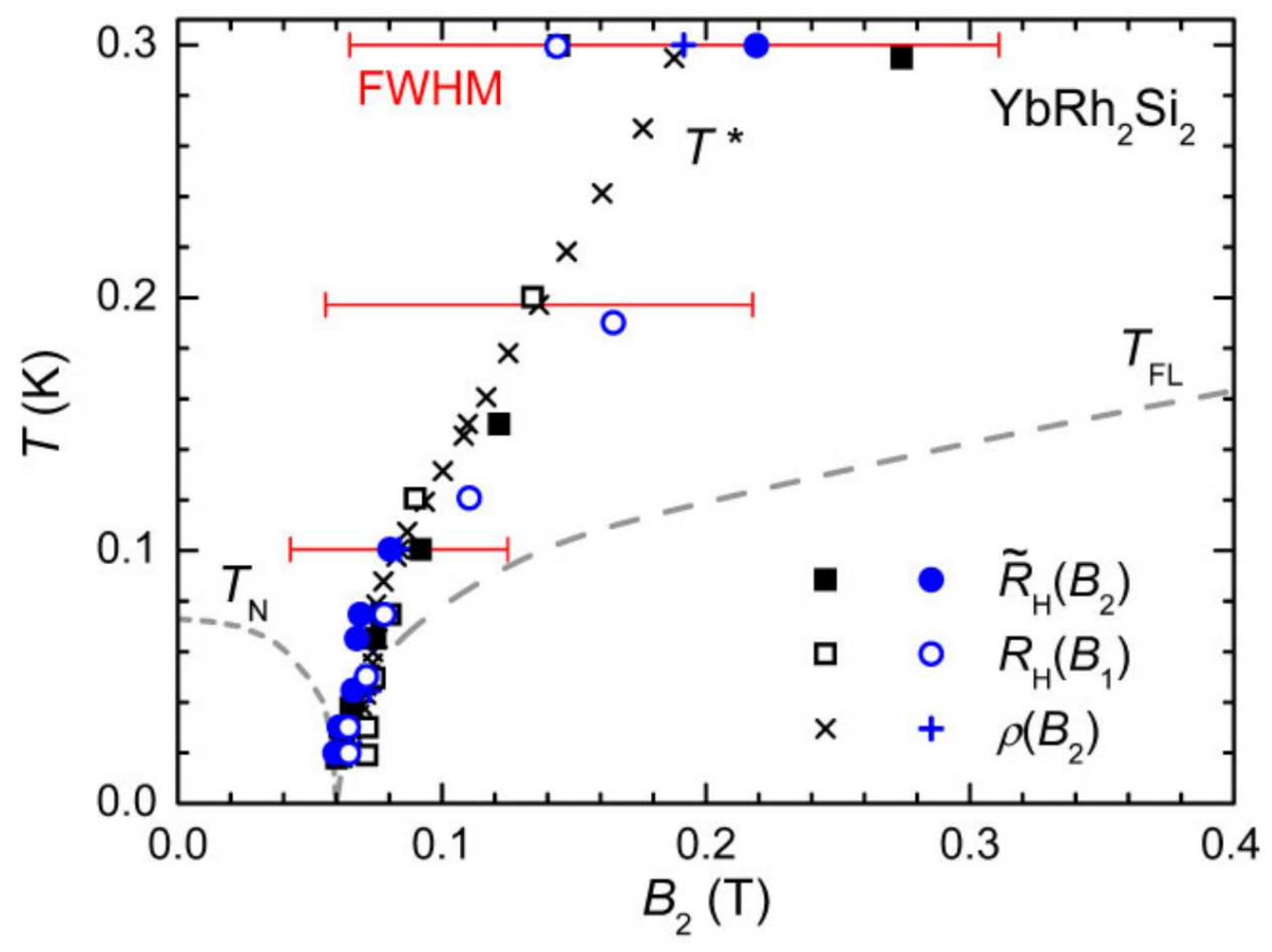

FIGURE 5: Temperature-magnetic field phase diagram of $YbRh_2Si_2$ [1,8].

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Substrate

Germanium:

- Space group: F-43m
- Cubic diamond structure
- Lattice parameter: a = 5.646 Å

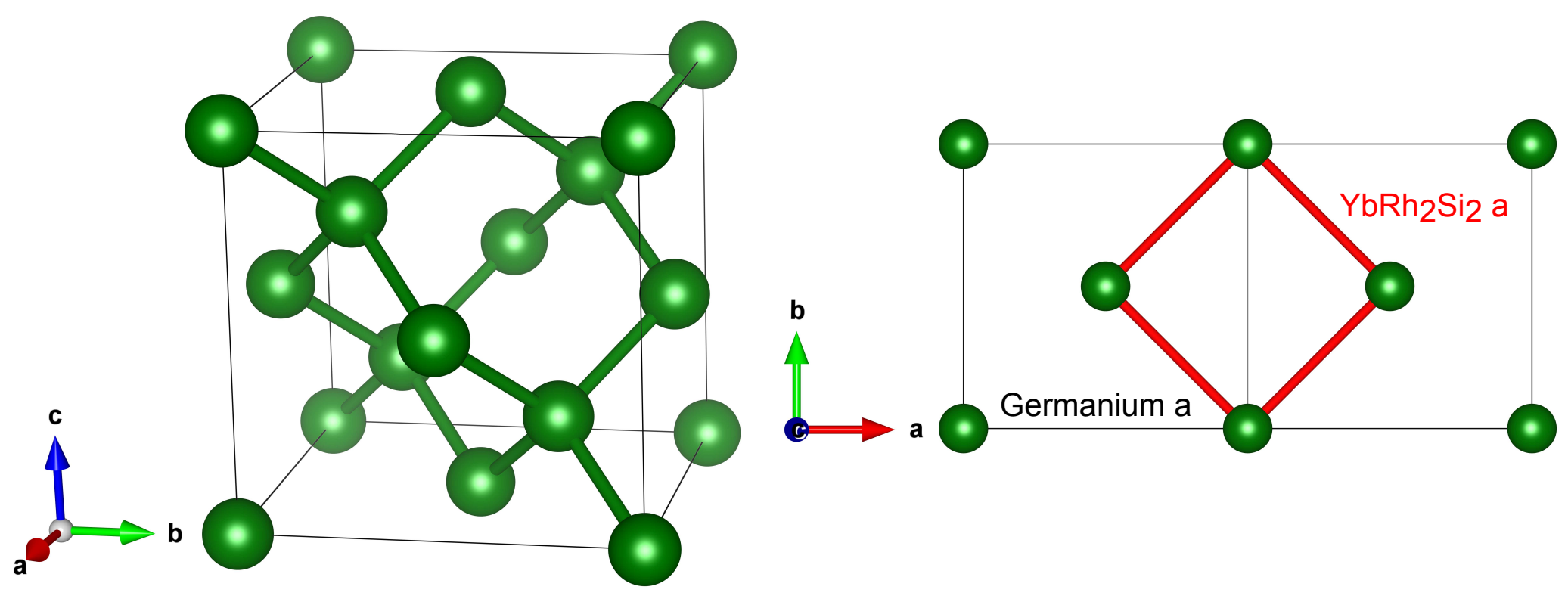

FIGURE 6: Unit cell of Germanium on the left and lattice matching of Germanium and $YbRh_2Si_2$ on the right.

- For successful growth in an MBE setup the lattices of the substrate and the desired compound typically have to be matched to within 2% of each other. The base plane of $YbRh_2Si_2$ has an excellent lattice match to the face centered atoms in the Germanium unit cell.

First results

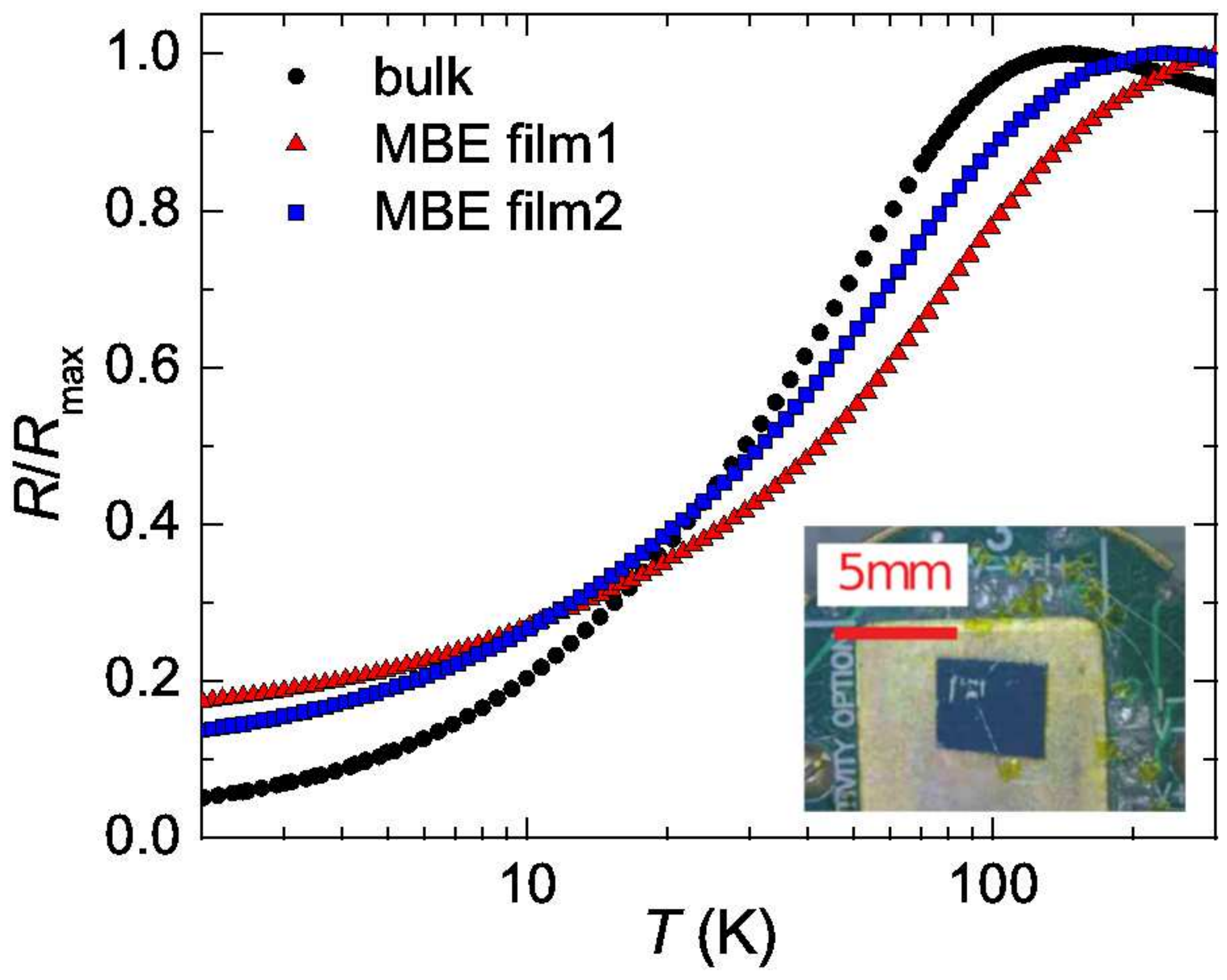

FIGURE 7: Temperature-dependent electrical resistivity, normalized to its maximum, of two MBE grown YbRh2Si2 films and a bulk sample for comparison. Insert: Photograph of MBE film2 contacted by wire bonding.

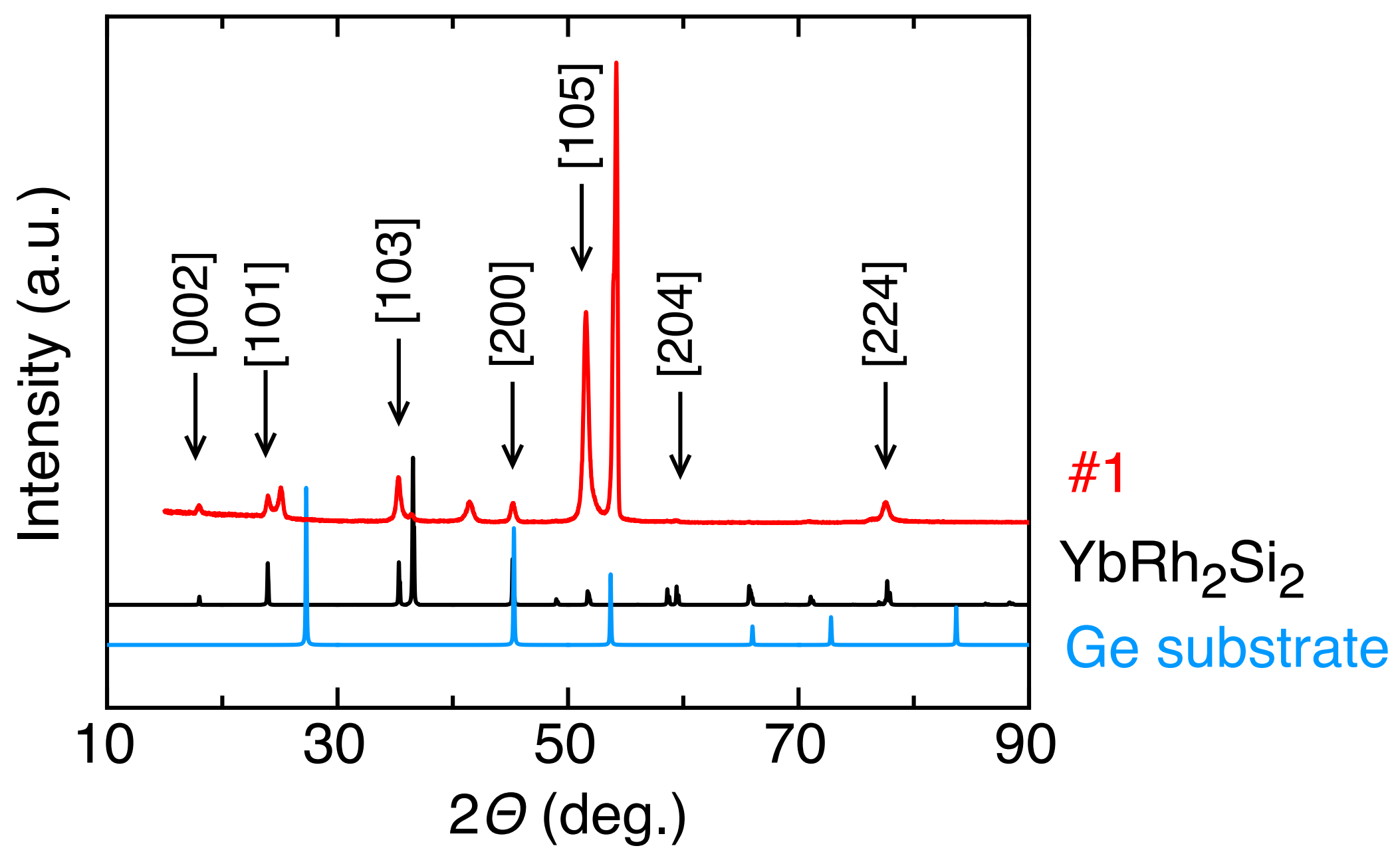

FIGURE 8: X-ray data of MBE film2 confirming that the film has the correct crystal structure.

Outlook

- Further improvement of film quality
- Investigation of thickness dependence of electrical transport
- Inclusion of films in microwave cavity

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