SICORP EU final summary

Project title : Establishing the basic science and technology for iron-based superconducting electronics applications (IRON-SEA)
Coordinator of the EU part of the project : Kazumasa Iida (IFW-Dresden)
Coordinator of the Japanese part of the project : Hiroshi Ikuta (Nagoya University)
Project period : October 1, 2012 – September 30, 2014 (EU)
October 1, 2012 – March 31, 2015 (Japan)

Consolidated public summary in English

Title of the project

Establishing the basic science and technology for iron-based superconducting electronics applications

Catchy title of the project

Paving the way for future device applications of Fe-based superconductors

Title 1: shows the general objective of the project and the main issues raised

Preparation of thin films with high quality, fabrication of several types of junction, and study of the fundamental properties using the thin films

The discovery of high-temperature superconductivity in Fe-based materials triggered enormous research activities worldwide. The highest critical temperature (T_c) is 56 K at the point of this report, the second highest record next to the cuprate superconductors. Moreover, they have a smaller anisotropy and probably a *s*-wave symmetry unlike the cuprates that suggest the difficulties the cuprate superconductors are encountered with in device applications are probably not severe in Fe-based superconductors (FeSCs). However, no well-organized study on their potential in electronic applications had been carried out before the start of this project. This project had addressed three major topics, thin film preparation, junction fabrication, and physical property measurements to explore the possibility of future device applications of these materials. Besides the FeSCs, MgB_2 was also studied as they have the common feature of being a multi-band superconductor. When the present project started, thin films of the three major FeSC materials were already available, but there were a large room for improvements. There were also materials that have relatively high T_c but were not available as thin films. Studies on junction fabrication were already reported, but the fabricated junctions were far from ideal. Much of the fundamental information that is related to device physics was still missing. The present project has addressed these issues.

During the project, the knowledge the partners have acquired in past studies, as well as the new results, were thoroughly discussed and shared in the consortium. This led to several new attempts of applying ideas that worked for other materials to the film preparation processes, and resulted in large improvement of the film quality. Here, it was also beneficial for the optimisation process that different groups at both sides of the consortium had worked together to characterize the thin films. The thin films fabricated in the consortium were used in the study of junction fabrication. Several insulating materials were put to test, in order to find a barrier layer that is ideal for FeSCs. Efforts were also devoted to the fabrication of a thin and smooth insulating layer to be used in an *in-situ* process. As another type of junction, grain boundary junctions were fabricated on various bicrystal substrates. The knowledge acquired on the course of the study on FeSCs was also applied to the junction fabrication of MgB_2, and resulted in a large improvement in the junction quality. As for the physical property measurements, the thin films fabricated in the consortium were provided to the other partners and various experimental techniques were applied. Single crystals that were grown for the purpose of referential experiments were also shared in the consortium. The theoretical groups in EU and Japan worked very closely by frequent internet discussion and mutual visits to develop an effective model to back up the experiments. A theoretical study was also carried out to propose experiments that may identify the gap symmetry, which is one of the central issues of the physics in FeSCs.

Project main results

Dramatic improvements have been seen in the quality of the thin films. *Ln*FeAs(O,F) (*Ln*=Nd, Sm, La, *Ln*1111 hereafter) films, which could be prepared only by a two-step method before this project, can be prepared now by a direct growth method that is much more simple. The quality of Fe(Se,Te) (11), Co-doped $BaFe_2As_2$ (Co-Ba122), K-doped $BaFe_2As_2$ and $SrFe_2As_2$ (K-Ba122, K-Sr122) thin films were also drastically improved. Thin films of P-doped $BaFe_2As_2$ (P-Ba122) and $CaFe_2As_2$ (Ca122) were realized for the first time. A new technique to grow MgB_2 was developed, with which thin films with a large area can be easily obtained.

New barrier materials were employed as the insulating layer to prepare FeSC-based junctions. A particularly large improvement in the fundamental parameter I_cR_n product was achieved with TiO_x. A method to grow a smooth and flat CaF_2 barrier layer that can be employed in an *in-situ* process of junction fabrication was developed. Various FeSCs were successfully prepared on [001]-tilted bicrystal substrates, from which we prepared bicrystal junctions. We have observed Shapiro steps for 11, Co- and P-Ba122 bicrystal junctions.

Additionally, it was found that P-Ba122 has a very high critical current density across the grain boundary. We also measured hybrid junctions between MgB_2 and P-Ba122. Thorough investigation and survey of other possible electronic applications were also carried out that yielded the conclusion that FeSCs are promising materials in other applications as well, like nanowire single-photon detector.

The physical properties were investigated using various techniques that include point-contact Andreev reflection, terahertz, optical, and femtosecond spectroscopy. Various transport measurements were also carried out such as noise spectroscopy, measurements of magnetoresistance, Hall coefficient, and critical current density under an extremely high dc magnetic field up to 45 T. Theoretical studies played an important role in interpretation of experimental results obtained in the consortium such as Andreev reflection spectroscopy, pump-probe spectroscopy, and Josephson effect measurements. Further, experiments that can identify the gap symmetry of FeSCs, which is one of the current central issues of debate, were proposed theoretically. A microscopic model for impurity scattering in multiband superconductors with $s\pm$ or $s++$ symmetry state was proposed, which also would aid to identify the gap symmetry.

Many of these results were obtained by a close and tight collaboration between the two sides of the consortium. Many possibilities for future collaboration were born from the present project, some of which are already developed in a new funded collaboration project.

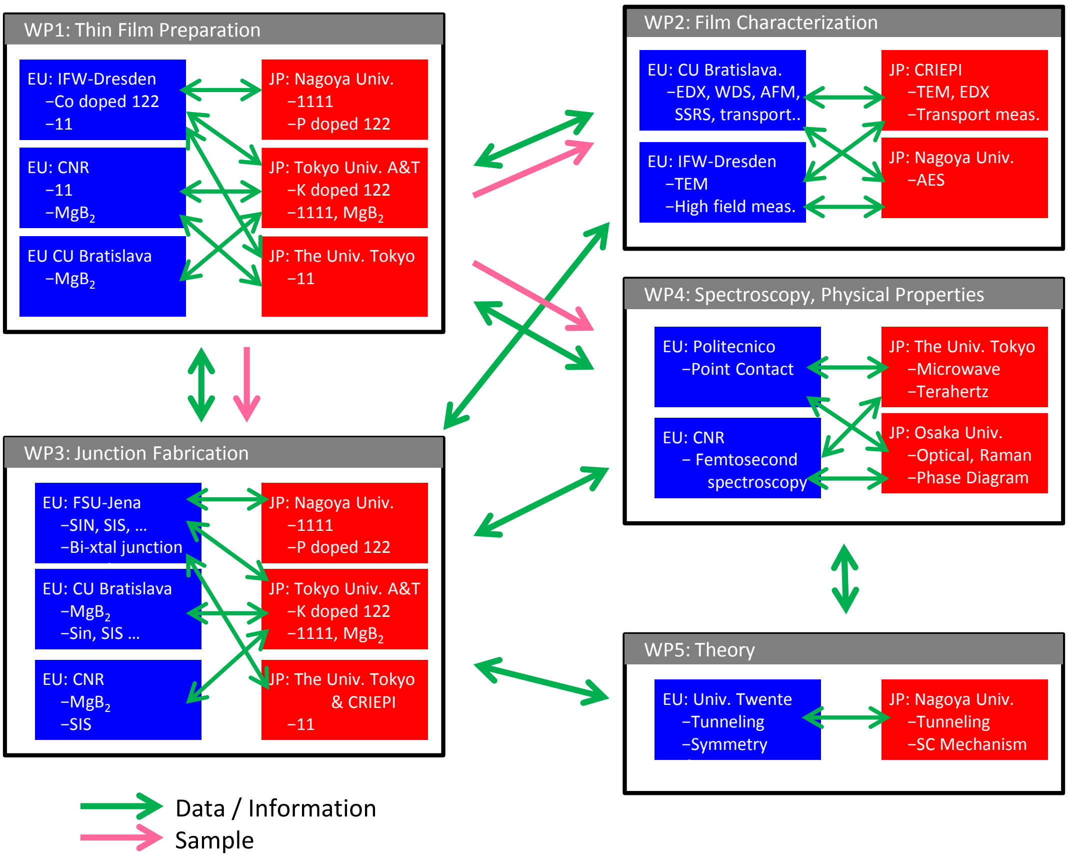
Added Value from International collaborative work

Prior to the project, there was already collaboration between some of the partners. The thin films preparation group in Nagoya University had collaboration with IFW Dresden, and the theoretical group in Nagoya University with the University of Twente. There was also collaboration between groups within each region. However, these pre-existing collaborations were limited to a rather narrow area of research. The present project had strengthened and vastly extended the pre-existing collaborations, and brought together researchers working on similar materials but in different field. Without the tight and close international collaboration, the results described above were hardly achieved. It is also worth to mention that the project provided young researchers the precious opportunities of working in an international project. Exchange of young scientist, as well as attending the project meetings had motivated them strongly that resulted in an improvement of the quality of their study.

Scientific production and patents since the beginning of the projects

IRON-SEA created a large number of high level results that is highly recognized by the research community. As a proof, IRON-SEA members gave a tremendous numbers of invited talks (59) at conferences in the three year period of the project. Additionally, 106 peer review papers have been published. Many of these papers were published in high profile journals such as Nature Communications, Scientific Reports, Physical Review and Applied Physics Letters. The results were also disseminated by frequent presentation in international as well as domestic conferences.

Illustration



Factual information

The IRON-SEA project is a fundamental research project coordinated by Dr. Kazumasa Iida (IFW Dresden, now associate professor at Nagoya University) in EU and by Prof. Dr. Hiroshi Ikuta (Nagoya University) in Japan. It associated Prof. Dr. Paul Seidel (Friedrich-Schiller-Universität Jena), Prof. Dr. Michio Naito (Tokyo University of Agriculture and Technology), Prof. Dr. Andrej Plecenik (Comenius University Bratislava), Prof. Dr. Atsutaka Maeda (The University of Tokyo), Prof. Dr. Renato Gonnelli (Politechnico di Torino), Prof. Dr. Setsuko Tajima (Osaka University), Prof. Dr. Sergio Pagano (Consiglio Nazionale Delle Ricerche), Dr. Ichiro Tsukada (Central Research Institute of Electronic Power Industry), Prof. Dr. Alexander Golubov (University of Twente), and Prof. Dr. Yukio Tanaka (Nagoya University). The project started on 01.10.2011 and lasted 36 months in EU and 42 months in Japan. EU grant amounted to €1,684,540 and JST grant amounted to ¥151,600,000.

Consolidated public summary in Japanese

Title of the project

鉄系超伝導体デバイスの基盤技術の構築

Catchy title of the project

鉄系超伝導体の将来におけるデバイス応用に向けて

Title 1: shows the general objective of the project and the main issues raised

高品位薄膜の作製、これらの薄膜を用いた様々な接合の作製、および基礎物性の研究

鉄系超伝導体における高温超伝導の発見をきっかけに、世界的に極めて活発な研究が展開されている。この報告書作成時点での超伝導転移温度(T_c)は最高で 56 K であり、銅酸化物超伝導体に次ぐ記録である。さらに、鉄系超伝導体は異方性が銅系に比べ小さく、超伝導対称性はおそらく *s* 波であると考えられている。これらの点から、銅系超伝導体がデバイス応用上で直面している多くの困難が、鉄系超伝導体ではそれほど深刻でない可能性が考えられる。しかし、デバイス応用における鉄系超伝導体の可能性を探る組織的な研究は、本プロジェクト開始時には、まだ存在していなかった。本プロジェクトでは、これらの材料のポテンシャルを探るために、薄膜成長、接合作製、および物性測定の 3 つの点から研究を実施した。また、鉄系同様に多バンド超伝導体である MgB_2 も、研究対象とした。研究開始時には、鉄系超伝導体の主たる三物質系の薄膜は既に得られていたが、膜質の面からはまだ大きな改善の余地があった。また、比較的 T_cの高い物質で、薄膜が実現していなかった系もあった。接合作製の報告も既にあったが、作製されていた接合は理想からほど遠いものであった。デバイス物理の観点から重要な多くの基礎的な物性データも不足していた。本研究では、これらの点に焦点をあてて研究を進めた。

プロジェクトを進めるにあたり、各グループが過去に得ていた知見や、プロジェクトにより得た新たな成果を徹底的に議論し、グループ間で共有した。このことにより、他の系で有効だった手法をそれぞれの薄膜成長で試みることが出来、結果的に膜質の大きな向上につながった。EU-日本双方のグループが協力して薄膜の評価を行ったことも、成長プロセスの最適化を行う上で非常に有効であった。鉄系超伝導の接合作製ではバリア層の候補となる様々な物質を試した。また、*in-situ* での接合作製に適用可能な、平坦な絶縁薄膜の作製プロセスの研究も進めた。さらに、双晶基板を用いた双晶接合の作製も行った。鉄系超伝導体の研究で得られた知見は MgB_2 にも適用され、従来の接合に比べて著しく改善された高品位な接合の作製に成功した。基礎物性測定には、本プロジェクト内で作製された薄膜に様々な測定技術を適用した。参照実験のために単結晶の作製も行い、プロジェクト内での共同研究に用いた。EU と日本側の理論グループは頻繁なインターネットを介したディスカッションや相互訪問

などで非常に密接に共同研究を進め、実験をバックアップするための有効モデルの構築などを行った。また、現在、鉄系超伝導体における議論の的の一つである超伝導対称性を判別するための実験を提案するために、理論的考察を行った。

Project main results

本プロジェクトでの研究により、薄膜の膜質は大きく向上した。*Ln*FeAs(O,F) (*Ln*=Nd, Sm, La, 以降は *Ln*1111)薄膜の作製には、以前は 2 ステップでの成長プロセスが必要であったが、より単純な 1 ステップでの成長が可能になった。Fe(Se,Te) (11)、Co ドープ $BaFe_2As_2$ (Co-Ba122)、K ドープ $BaFe_2As_2$ または $SrFe_2As_2$ (K-Ba122, K-Sr122)薄膜の膜質も大きく改善した。また、P ドープ $BaFe_2As_2$ (P-Ba122) や $CaFe_2As_2$(Ca122)系薄膜を初めて実現することができた。さらに、大面積成長に適した、MgB_2 薄膜の成長手法も開発した。

鉄系超伝導体の接合作製ではバリア層に新たな材料を適用した。特に、TiO_x を用いることで、基本的なパラメータである I_cR_n 積を大きく向上させることが出来た。接合の *in-situ* 作製に向けたバリア層の成長では、CaF_2 層の平坦化に成功した。さらに、双晶基板上に様々な鉄系超伝導体の薄膜を成長して双晶接合を作製し、11 系、Co-Ba122、および P-Ba122 系でシャピロステップの観測に成功した。また、P-Ba122 結晶粒界での臨界電流密度が非常に高いことを見出した。さらに、MgB_2 と P-Ba122 の間のポイントコンタクトの測定も初めて成功した。一方、鉄系超伝導体の他の応用の可能性を探る研究からは、ナノワイヤ単一光子検出器としての応用が有望であるとの結論を得た。

基礎物性の測定には、アンドレーエフ反射分光、テラヘルツ分光、光学測定、フェムト秒分光など、様々な手法を適用した。磁気抵抗やホール係数、45 T までの高磁場での臨界電流密度など、様々な輸送特性の測定も行った。一方、アンドレーエフ反射分光、ポンプ・プローブ分光、ジョセフソン効果の測定などの実験を解釈する上で、理論的研究が重要な役割を果たした。さらに、現在議論の的になっている超伝導対称性を判別するための実験を、理論的考察に基づいて提案した。また、*s*± および *s*++ 対称性の多軌道超伝導体における不純物散乱の微視的なモデルを構築したが、この結果を適用することで超伝導対称性を議論することも可能である。

これらの成果の多くは、EU 側と日本側の密接な共同研究によって得られたものである。また、将来の共同研究の可能性も多く生まれた。実際、その一部は新たなプロジェクトに取り込まれ、共同研究プロジェクトの獲得に発展した。

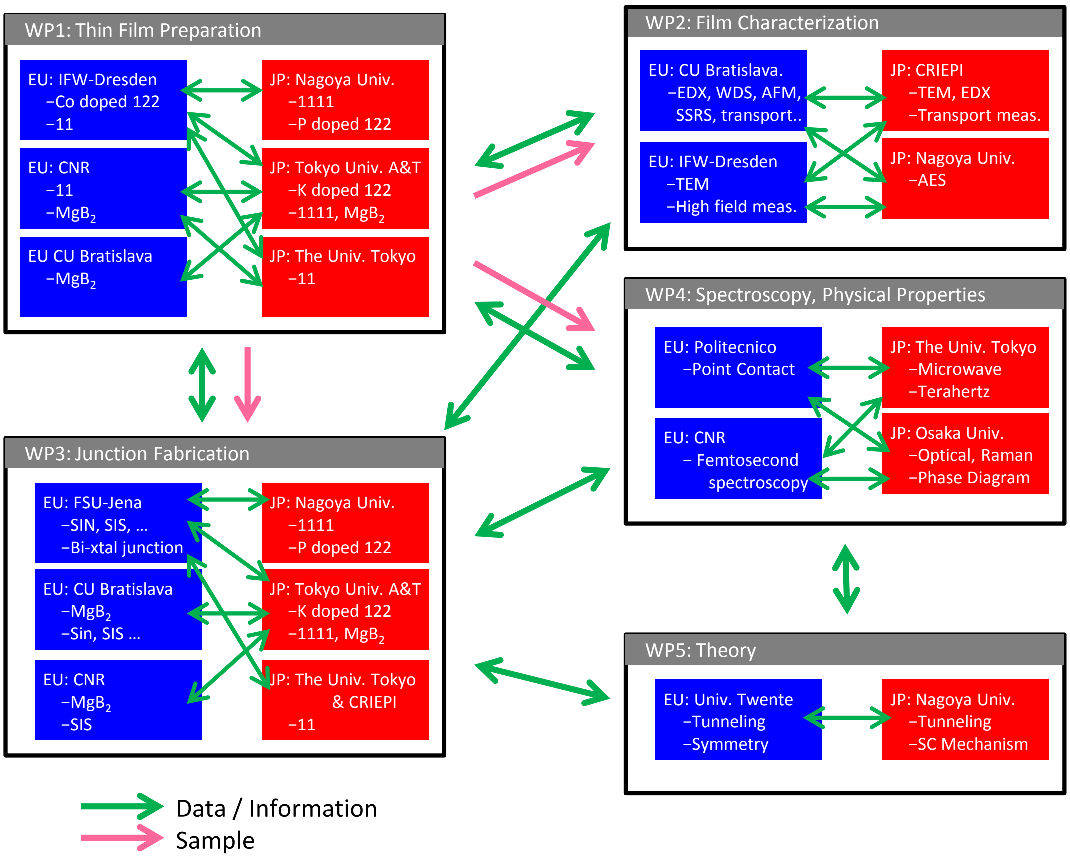
Added Value from International collaborative work

本プロジェクト開始以前にも、メンバーの一部は共同研究を行っていた。例えば、名古屋大学のグループは IFW Dresden と薄膜成長で共同研究を行い、別の名古屋大学のグループは Twente 大学と理論での共同研究を行っていた。それぞれ EU 内、もしくは日本内での共同研究もあった。しかし、これらは比較的限られた共同研究であった。本プロジェクトにより、これまでの共同研究を強化し、さらに大きく拡張することが出来、同じ系を異なる手法で研究する様々な研究者の間での共同研究が可能になった。これまでに述べた成果は、この国際的な共同研究無くしては、到底、達成することは不可能であった。本プロジェクトはまた、若手研究者に国際的なプロジェクトに関わるという貴重な機会をもたらした。他グループへの派遣や、プロジェクトミーティングへの出席は、若手研究者にとって大きな動機づけとなり、研究の質を向上させるのにも大きく寄与した。

Scientific production and patents since the beginning of the projects

本プロジェクトにより、多くの優れた成果が生まれ、このことは広く認知されている。例えば、本プロジェクトの 3 年間で、メンバーは合計 59 回の招待講演を行っている。さらに、107 報の査読論文が出版された。これらの論文の多くは、Nature Communications、Scientific Reports、Physical Review や Applied Physics Letters などの高水準な学術誌に掲載された。また、研究成果を広く普及するために、数多くの国際会議や国内学会での講演を行った。

Illustration



Factual information

IRON-SEAプロジェクトは、EU側はKazumasa Iida博士 (IFW Dresden, 現名古屋大学)、日本側は生田博志教授(名古屋大学)を代表者とする基礎研究プロジェクトである。参加した研究者は、Paul Seidel 教授 (Friedrich-Schiller-Universität Jena), 内藤方夫教授 (東京農工大学), Andrej Plecenik 教授 (Comenius University Bratislava), 前田京剛教授(東京大学), Renato Gonnelli 准教授 (Politechnico di Torino), 田島節子教授(大阪大学), Sergio Pagano 准教授 (Consiglio Nazionale Delle Ricerche), 塚田一郎博士(電力中央研究所), Alexander Golubov 准教授 (University of Twente)および田仲由喜夫教授(名古屋大学)である。プロジェクトは 2011 年 10 月 1 日に開始され、EU 側は 36 ヶ月、日本側は 42 ヶ月の研究期間であった。EU 側の研究費は 1,684,540 ユーロ、JST 側は 151,600,000 円であった。