## 2024

**FeRh thin film research.** Recent advances in FeRh thin-film technology have enabled the fabrication of complex magnetic structures, such as multilayered and patterned films. These structures have potential applications in spintronics, magnonics, and other areas of nanotechnology.

Reversible control of magnetism was studied on an initially fully magnetic B2 FeRh thin film. Subsequent irradiation by 120 keV $Ne^+$ ions turned the thin film completely to the paramagnetic A1 phase. Repeated annealing at 300 °C for 60 min resulted in 100 % magnetic B2 phase, demonstrating a process that is both reversible and repeatable [1].

Magnetic nanopattern was successfully created in FeRh film by means of nanolithography. Different fluences ($10^{15}$ and $10^{16}$ ions/cm$^2$) of 110 keV energy neon ion irradiation were applied to project the mask geometry in the magnetic structure of the sample. From the results, for the first time, we constructed the 3D visualization of the created individual magnetic domains (Figure 1) [2].

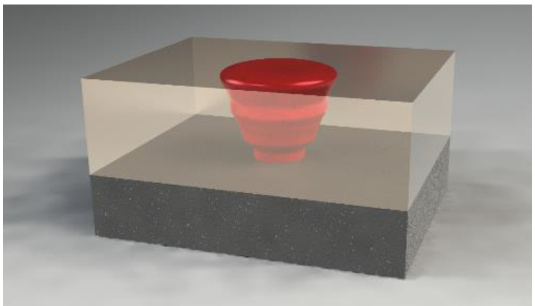

Figure 1. 3D visualization of the shape of magnetic domain in an FeRh thin film obtained after $10^{15}$ ion/cm$^2$ $Ne^+$ irradiation through spherical polystyrene mask. The red region represent the ferromagnetic ordering in a paramagnetic matrix

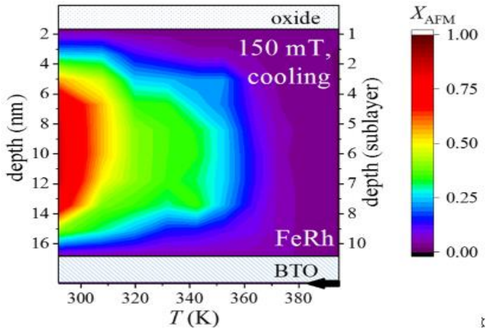

Figure 2. *The in-depth antiferromagnetic ratio ($X_{AFM}$) as a function of temperature with applied 150 mT magnetic field in an FeRh thin film.*

The effect of laser irradiation (20–200 mW) was studied on a 109 nm $Fe_{51}Rh_{49}$ film grown on an MgO (100) substrate. Initial paramagnetic A1 structure was achieved after 120 keV $Ne^+$ ion irradiation (fluence: $1 \times 10^{16}$ ions/cm²) as it was confirmed by Mössbauer spectroscopy. Higher powers caused physical damage, while lower powers revealed a magnetic structure matching the laser pattern via magnetic force microscopy [3].

Grazing-incidence nuclear scattering experiments were performed on FeRh/$BaTiO_3$. Our results revealed significant synergistic and antagonistic relationships in the achievable ferromagnetic or antiferromagnetic phase ratios when the heterostructure was effected by electric and/or magnetic fields during the temperature changes (Figure 2) [4].

Self-diffusion of iron in FeRh was investigated. By using neutron reflectivity technique, the pre-exponent factor and activation energy was determined as $D_0 = (1.19 \pm 0.5) \times 10^{-16}$ m$^2$s$^{-1}$ and $E_a = (1.00 \pm 0.03)$ eV respectively [5].

To study the A1 to B2 structural and magnetic transitions in an isotope-periodic FeRh film, non-destructive techniques like X-ray diffraction, Mössbauer spectroscopy, and neutron reflectometry were used. Analysis revealed changes in lattice parameters, grain sizes, and hyperfine parameters during the transformation. Neutron reflectometry indicated no significant long-range diffusion, suggesting a local atomic interchange. [6].

**Ion-beam-induced luminescence.** Lots of materials, like e.g., insulators emit light when irradiated by an ion beam. The light can be collected and analysed, i.e., ion-beam-induced luminescence (IBIL) method can be utilized. IBIL is a powerful analytical tool to analyse various types of defects in a wide range of materials.

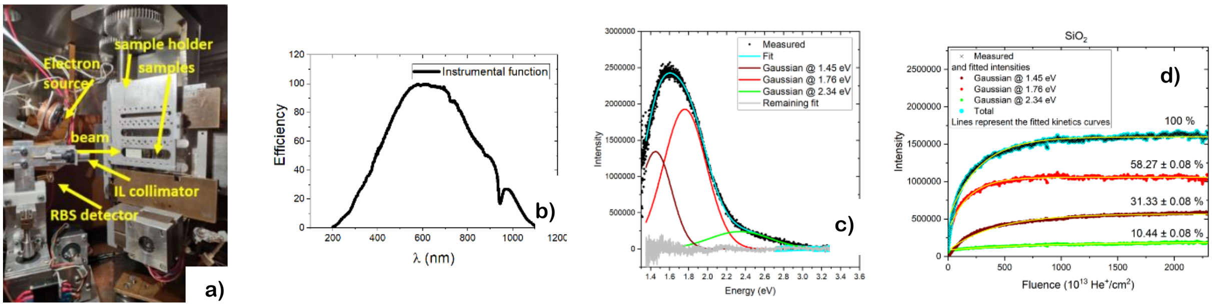

*Figure 3. a) IBIL setup, b) Instrumental function of the setup, i.e., the spectral efficiency were determined by using halogen and deuterium calibration lamps, c) IBIL spectrum of the silica quartz single crystal transformed to energy scale. The spectra decomposition is also shown. d) Fluence evolution of the various defect intensities.*

A single crystalline (0001) α-$SiO_2$ (quartz) sample has been investigated by IBIL method as shown in Figure 3. In this case, intense emitted light can be observed when a 2 MeV $He^+$ beam reaches the quartz sample. The importance of methodological issues in the IBIL measurement (including set-up, sample holder and proper beam settings) was discussed in ref. [7].

To perform accurate data evaluation, the instrumental function of the applied IL set-up (collimator, optical fibers and spectrometer) has to be determined by mean of calibration light source (Figure 3. b) and has to be taken into account. After the necessary corrections, the IL spectra have to be transformed to the energy scale, where the decomposition can be made by the Gaussian (or Breit-Wigner) function to find the corresponding transitions energies.

In the IBIL spectra of silica quartz (Figure 3.c), three emission bands were found at 1.45 eV, 1.76 eV and 2.34 eV, the corresponding defects were identified as an unknown origin, non-bridging oxygen hole centres (NBOHC), and self-trapped excitons (STEs), respectively. The evolution of the defect-related IL peaks was determined as a function of $He^+$ irradiation fluence. The observed trends (Figure 3.d) are due to the simultaneous formation of various defect centres and their possible interactions during the ion-beam irradiation process. The saturated values can be explained by the nature of defect dynamic equilibrium provided by the ion beam. However, these values depend on the beam settings, beam current, etc., so instead of their absolute values only their relative saturated values can be compared.

The research data of ref. [7] are available in the HUN-REN Data Repository Platform under DOI: 10.5158/ARP/N6ODFL.

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[1] Merkel DG, Lengyel A, Nagy DL, Németh A, Horváth ZsE, Bogdán Cs, Gracheva MA, Hegedűs G, Sajti Sz, Radnóczi GyZ, Szilágyi E: Reversible control of magnetism in FeRh thin films. SCIENTIFIC REPORTS 10 : 1 Paper: 13923 , 11 p. (2020) DOI: https://doi.org/10.1038/s41598-020-70899-x

[2] Merkel D.G., Hegedüs G., Gracheva M., Deák A., Illés L., Németh A., Maccari F., Radulov I., Major M., Chumakov A.I., Bessas D., Nagy D.L., Zolnai Z., Graning S., Sájerman K., Szilágyi E., Lengyel A.: A Three-Dimensional Analysis of Magnetic Nanopattern Formation in FeRh Thin Films on MgO Substrates: Implications for Spintronic Devices. ACS APPLIED NANO MATERIALS 5 : 4 pp. 5516-5526. , 11 p. (2022) DOI: https://doi.org/10.1021/acsanm.2c00511

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[3] Merkel D.G., Sájerman K., Váczi T., Lenk S., Hegedűs G., Sajti S., Németh A., Gracheva M.A., Petrik P., Mukherjee D., Horváth Z.E., Nagy D.L., Lengyel A.: Laser irradiation effects in FeRh thin film. MATERIALS RESEARCH EXPRESS 10 : 7 Paper: 076101 , 7 p. (2023) DOI: https://doi.org/10.1088/2053-1591/ace4a3

[4] Lengyel A., Bazsó G., Chumakov A.I., Nagy D.L., Hegedűs G., Bessas D., Horváth Z.E., Nemes N.M., Gracheva M.A., Szilágyi E., Sajti S., Merkel D.G.: Synergy effect of temperature, electric and magnetic field on the depth structure of the FeRh/BaTiO3 composite multiferroic. MATERIALS SCIENCE AND ENGINEERING B - SOLID STATE MATERIALS FOR ADVANCED TECHNOLOGY 285 Paper: 115939 , 8 p. (2022) DOI: https://doi.org/10.1016/j.mseb.2022.115939

[5] Merkel D.G., Sajti S., Deák L., Hegedűs G., Horváth Z.E., Lengyel A.: Iron self-diffusion in B2-FeRh thin film. VACUUM 218 Paper: 112617 , 5 p. (2023) DOI: https://doi.org/10.1016/j.vacuum.2023.112617

[6] Merkel D.G., Gracheva M.A., Radnóczi G.Z., Hegedűs G., Nagy D.L., Horváth Z.E., Lengyel A.: Temperature induced A1 to B2 structural and magnetic transition in FeRh thin film. MATERIALS RESEARCH EXPRESS 11 : 8 Paper: 086403 , 7 p. (2024) DOI: https://doi.org/10.1088/2053-1591/ad6f71

[7] Szilágyi E., Pal M.K., Kótai E., Zolnai Z., Bányász I.: Fluence evolution of defects in α-SiO2 determined by ionoluminescence. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION B-BEAM INTERACTIONS WITH MATERIALS AND ATOMS 555 Paper: 165470, 7 p. (2024) DOI: https://doi.org/10.1016/j.nimb.2024.165470