Supplementary information

Negative magnetoresistance in different nitrogen content $EuNbO_{3-x}N_x$ single-crystalline thin films

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Analysis of the nitrogen contents of thin films through RBS and ERDA

The N/Eu ratios of the films were accurately determined via Rutherford backscattering spectrometry (RBS) and elastic recoil detection analysis (ERDA) using the following steps:

1. First, as the stopping powers of RBS and ERDA are different, it is necessary to clarify the relation between the two powers by stoichiometric oxides. The ratio of the stopping power of RBS (Ω_{RBS}) to that of ERDA (Ω_{ERDA}) ($\Omega_{RBS}/\Omega_{ERDA}$) was estimated using ZnO for sample 1S ($EuNbO_{2.4}N_{0.6}$ film on STO) and sample 2S ($EuNbO_{2.3}N_{0.7}$ film on STO) and ZrO_2 for sample 3S ($EuNbO_{2.0}N_{1.0}$ film on STO). As the ZrO_2 sample contained a small amount of Hf, we assumed that $N_{Zr} + N_{Hf} = 2$. $\Omega_{RBS}/\Omega_{ERDA}$ was determined according to the following formulae:

$$\frac{\Omega_{RBS}}{\Omega_{ERDA}} = \frac{N_O}{N_{Zn}} \frac{Y_{Zn}/\sigma_{Zn}}{Y_O/\sigma_O} \text{ for samples 1S and 2S}$$

$$\frac{\Omega_{RBS}}{\Omega_{ERDA}} = \frac{N_O}{N_{Zr}+N_{Hf}} \frac{Y_{Zr}/\sigma_{Zr}+Y_{Hf}/\sigma_{Hf}}{Y_O/\sigma_O} \text{ for sample 3S}$$

where N, Y, and σ are the number of atoms in the formula weight, total counts measured in the spectrum, and differential scattering cross section, respectively. The differential scattering cross section of each element was calculated using the SIMNRA program. Y_{Zn} and Y_{Hf} were obtained from the RBS spectrum and Y_O from the ERDA spectrum.

2. Eu/N was obtained by substituting the values of the stopping power ratio into the following formula:

$$\frac{N_N}{N_{Eu}} = \frac{Y_N/\sigma_N}{Y_{Eu}/\sigma_{Eu}} \frac{\Omega_{RBS}}{\Omega_{ERDA}}$$

where Y_{Eu} and Y_N were obtained from the RBS spectrum. N recoil spectra were extracted from the ERDA spectrum for each sample. The differential scattering cross section of each element was also calculated using the SIMNRA program, similar to the first step.

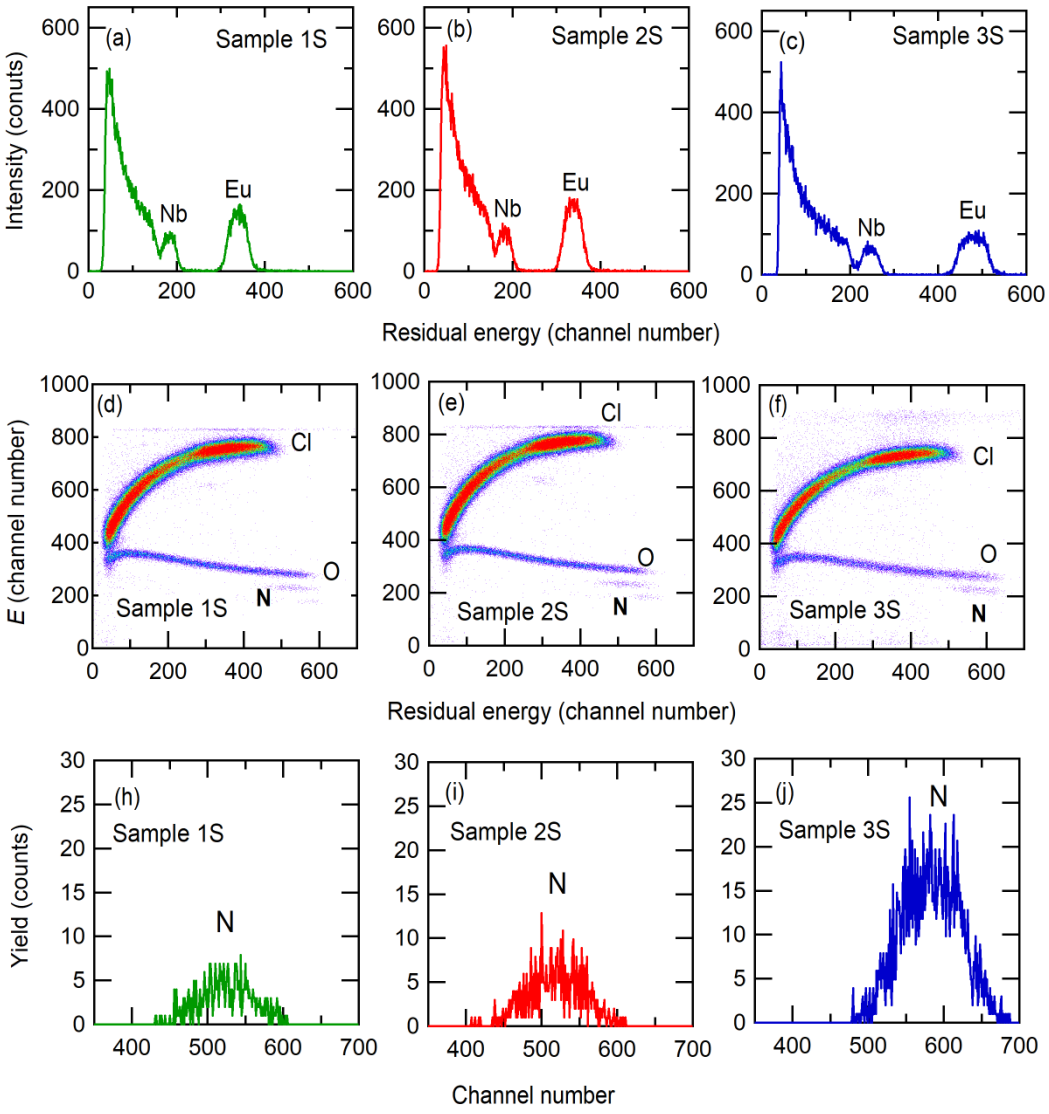

Figure S1. RBS spectra of samples (a) 1S, (b) 2S, and (c) 3S. *ΔE* vs. residual energy ERDA histograms of samples (d) 1S, (e) 2S, and (f) 3S. (h), (i), and (j) show the N recoil spectra extracted from (c), (d), and (e) respectively, which are obtained by integration along *ΔE*.

	Sample 1S	Sample 2S	Sample 3S
$\Omega_{RBS}/\Omega_{ERDA}$	8.93	8.93	9.77
Y_{Eu}	7233	8095	20749
Y_N	430	575	1805
σ_{Eu}	1044.8	1044.8	1044.8
σ_N	935	935	935
N_N/N_{Eu}	0.59	0.71	0.95

Table S1. Values of Y_N, Y_{Eu}, σ_N, σ_{Eu}, $\Omega_{RBS}/\Omega_{ERDA}$ and N_N/N_{Eu}.

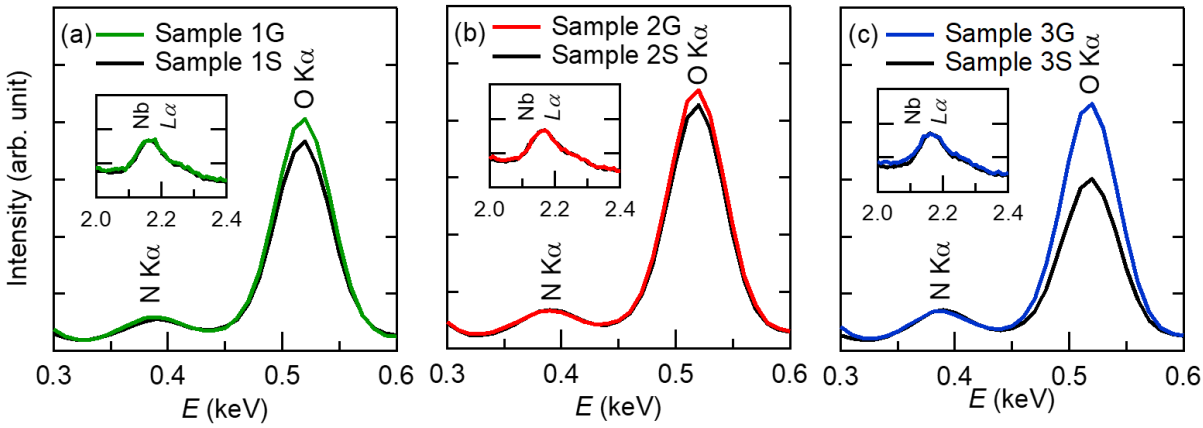

Figure S2. EDS spectra of the ENON films fabricated on GSO and STO, where each spectrum is normalized by the Nb *Lα* peak. (Insets show the Nb *Lα* peak of each spectrum.)

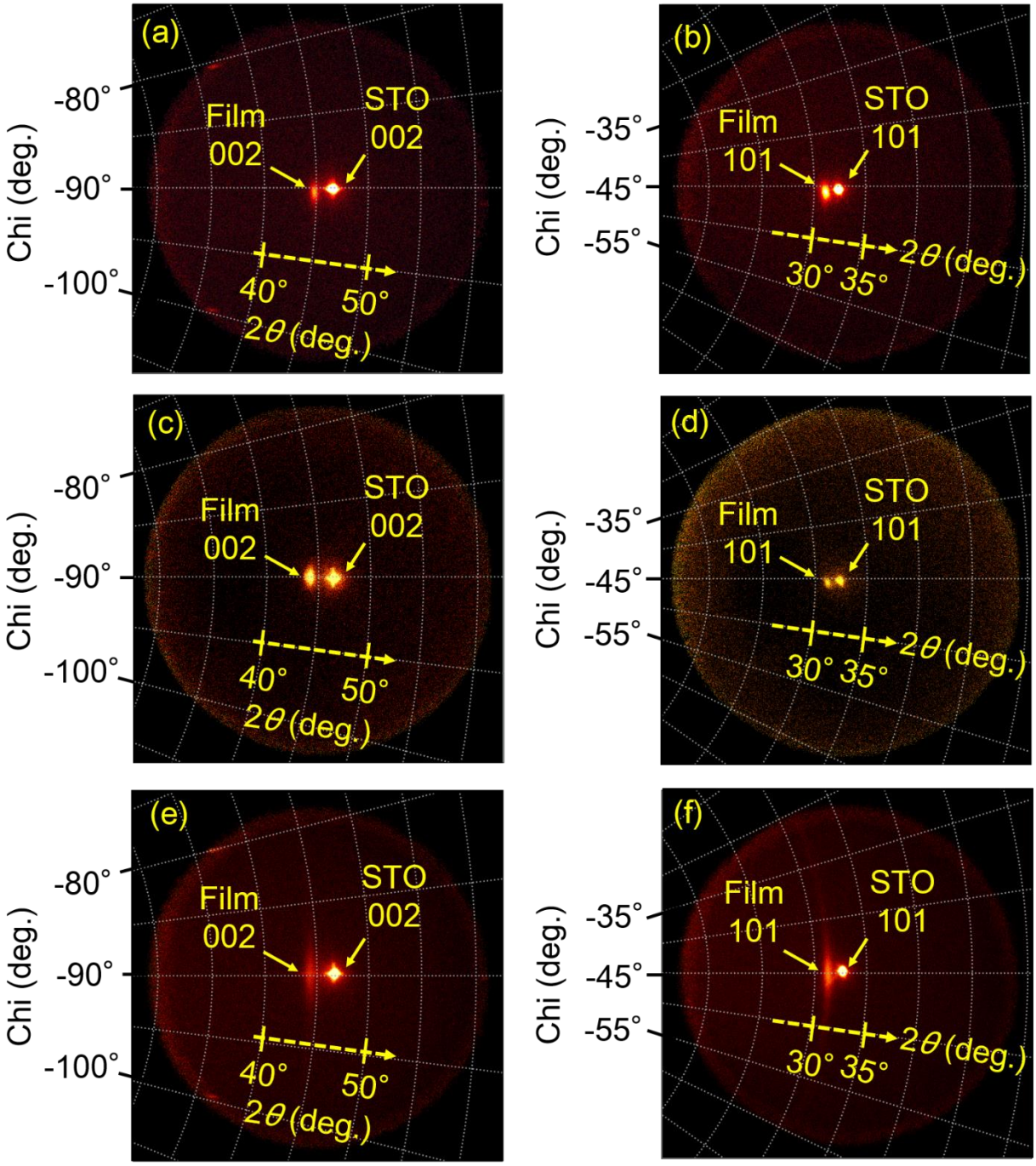

Figure S3. Two-dimensional 2θ–χ images of the (a, b) $EuNbO_{2.4}N_{0.6}$, (c, d) $EuNbO_{2.3}N_{0.7}$, and (e, f) $EuNbO_{2.0}N_{1.0}$ films deposited on STO at $\chi = 90°$ and 45°.

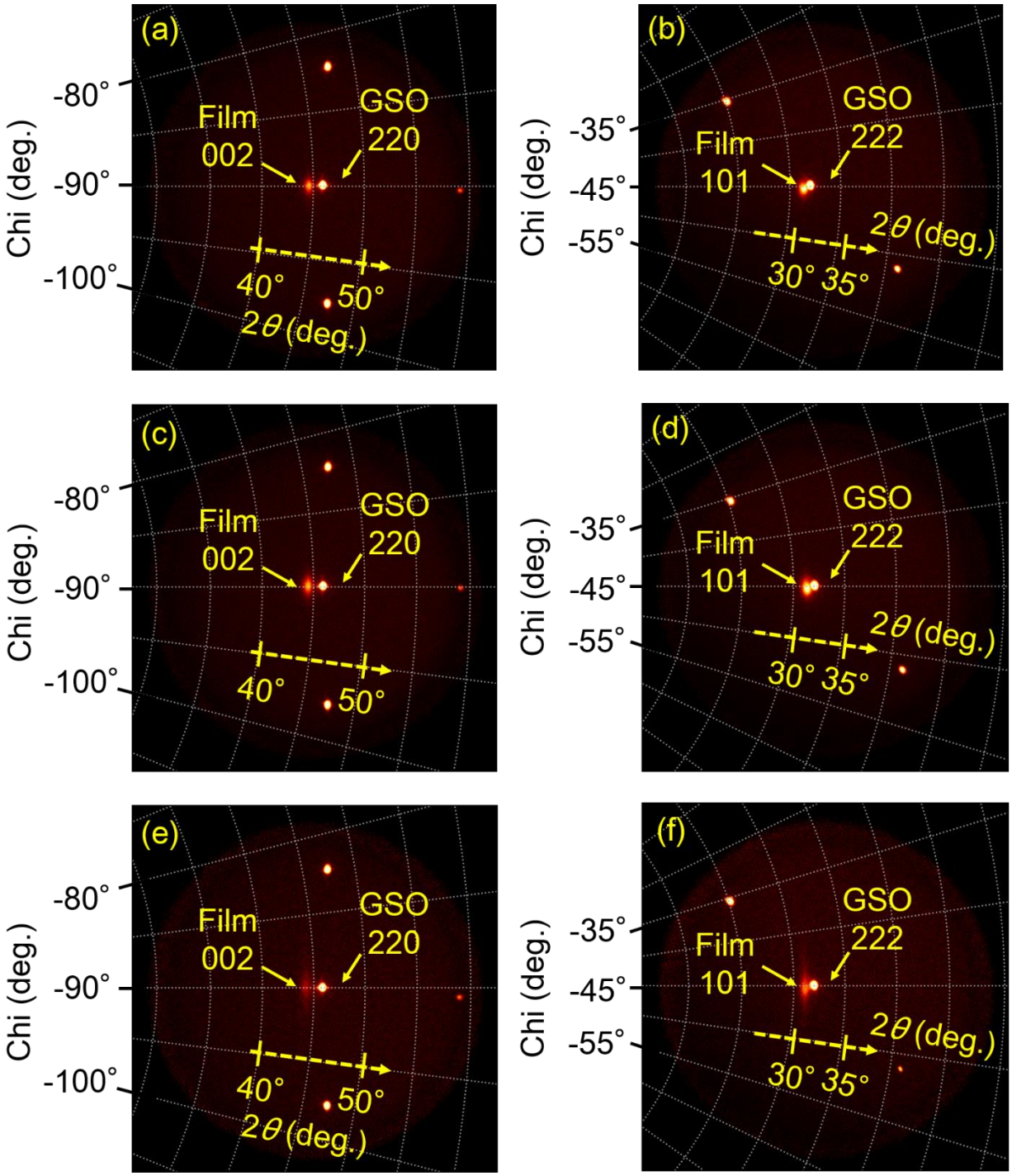

Figure S4. Two-dimensional 2θ–χ images of the (a, b) $EuNbO_{2.4}N_{0.6}$, (c, d) $EuNbO_{2.3}N_{0.7}$, and (e, f) $EuNbO_{2.0}N_{1.0}$ films deposited on GSO at χ = 90° and 45°.

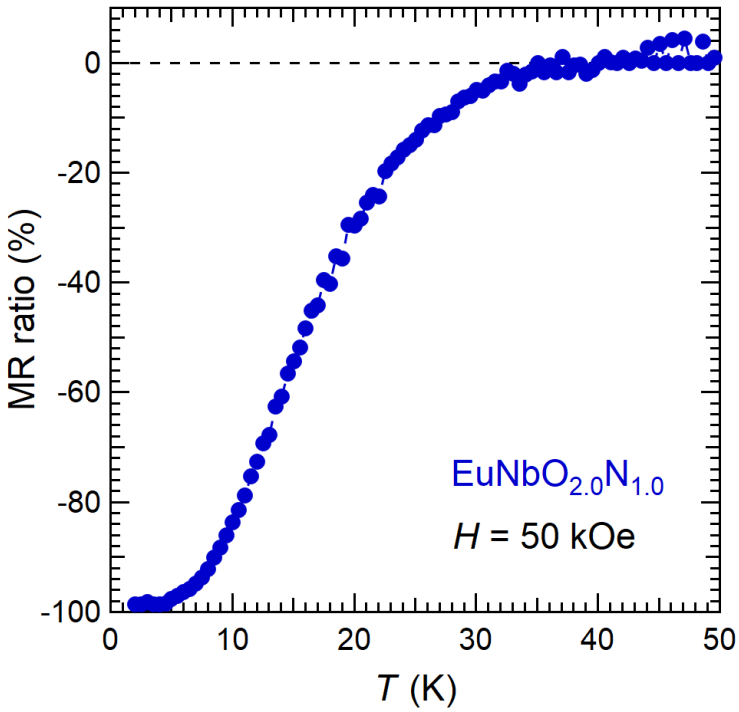

Figure S5. Temperature dependence of the MR ratio under 50 kOe for the $EuNbO_{2.0}N_{1.0}$ film deposited on GSO.