

## **Text S2. Characterization.**

SEM images were taken on a MIRA scanning electron microscope (Tescan, Czech). JEM 1200EX and JEM ARM200F (JEOL, Japan) were used to conduct TEM measurements. HAADF-STEM investigations were performed on a Titan Cubed Themis G2 300 with a probe corrector. XRD patterns were recorded on a D8 Focus (Bruker, Germany) diffraction instrument operating at 40 mA and 40 kV, using Cu K $\alpha$  as the radiation source ( $\lambda = 1.5405 \text{ \AA}$ ) in the continuous scanning mode. The  $2\theta$  scan range was from  $10^\circ$  to  $80^\circ$  in steps of 0.020 with a collection time of 0.2s per step. XPS measurements were carried out on a K-Alpha XPS machine (Thermo Fisher, America). Raman spectra were collected using a LabRAM-HR Evolution confocal Raman spectrometer with a 532 nm laser. The quantity of Co ions was determined by ICP-OES (PerkinElmer Optima 8300, USA) analysis. The XAS measurements, which encompass XANES and EXAFS spectra at the Co K-edge, were carried out on the sample at the 5S1 X-ray absorption beamline of Aichi Synchrotron Radiation Center. This beamline adopted a double-bounce channel-cut Si (111) monochromator for mono-beam X-ray absorption spectroscopy. The end-station is equipped with three ionization chambers and a seven-element SDD detector after the sample position for transmission and fluorescence mode X-ray absorption spectroscopy. The Athena and Artemis software packages were employed to process and analyze the spectra.