Temperature dependence of electron-phonon coupling and its correlation to ultrafast demagnetization

ABSTRACT

We report a systematic measurement of the electron-phonon thermalization timescales as a function of the sample base temperature in Ni using femtosecond electron diffraction. A strong temperature dependence has been observed in the vicinity of the Curie point. By assuming that ultrafast demagnetization completes well before the electron-phonon thermalization, this correlation between thermalization time and sample base temperature can be fit by a modified three temperature model describing the energy transfer among charge, spin, and phonon subsystems. The results indicate that charges and spins can be characterized by a unified temperature during ultrafast lattice heating.

EXPERIMENT SET-UP PROCESS

The experiments were conducted using a third generation femtosecond electron diffraction instrument with an increased electron beam energy up to 100 kV. Polycrystalline thin-film nickel samples with thickness of 22 ± 4.0 nm were prepared using a sputtering process and then mounted on TEM grids as free standing films. The TEM grids were placed inside the diffraction chamber. Structural dynamics of the nickel sample were recorded by capturing diffraction patterns at various pump-probe delay times.

PROCESS USED FOR DATA ANALYSIS

To obtain a quantitative measurement of structural dynamics, a recorded two-dimensional diffraction pattern was converted to a diffraction intensity pattern. Each Bragg peak in the intensity curve was fitted with a Gaussian line profile to determine its peak width. Finally the temporal evolution of the peak width was converted to temporal evolution of lattice temperature curve by applying a Debye-Waller factor. In the FED measurement, due to the residual heating of 1 kHz pump laser pulses, the actual sample temperature before time-zero is always higher than the pre-set stage temperature. This temperature shift due to the residual heating of 1 kHz pump laser pulses, the actual sample temperature before time-zero is always higher than the pre-set stage temperature. This temperature shift due to residual heat was determined by dividing the Bragg peak center shift with the linear thermal expansion coefficient (see figure 1).

Figure 1 shows a typical temporal evolution of lattice temperature as a function of pump-probe delay time. The curve displays a monotonous time dependence and can be well fitted by the equation: \[ T(t) = T_\infty + (T_0 - T_\infty) e^{-t/\tau} \]

\( T_\infty \) represents the overall temperature change of the lattice, \( T_0 \) is the time-zero point, and \( \tau \) is the time constant of lattice heating. We also found that lattice temperature increases by several hundred K in 10 ps as seen for a blue dotted line in figure 2. Such a jump becomes less prominent at higher excitation fluences (higher sample temperature jump) and also shifts its turning point towards the lattice heating time constant of 0.1 ps. The solid curves are the simulation results with assumption of ultrafast demagnetization, while the dotted curves are the ones assuming no ultrafast demagnetization.

CONCLUSIONS

We have studied the interaction dynamics among charge, spin and lattice subsystems in ferromagnetic nickel using femtosecond electron diffraction. By measuring rates of energy transfer as a function of sample temperature around the Curie point, we show that the demagnetization induced by fs optical excitation proceed in a timescale much faster than the lattice heating in ferromagnetic Ni. The huge jump of the e-ph coupling time constant around the Curie temperature reflects the large energy cost required to break magnetic ordering rather than a more complicated but more general Three Temperature Model is sufficient to describe the ultrafast energy transfer dynamics in ferromagnetic Ni. The huge jump of the e-ph coupling time constant around the Curie temperature reflects the large energy cost required to break magnetic ordering. The huge jump of the e-ph coupling time constant around the Curie temperature resembles very much the shape of the overall electron heat capacity changes in the vicinity of the Curie temperature. This temperature dependence of lattice thermalization time constant may very well be the origin of the overall electron heat capacity changes in the vicinity of the Curie temperature. As a result, the temperature increase of electrons and the magnetic ordering under the three temperature model is adequate to describe ultrafast lattice heating in nickel.

REFERENCES