# Superfluid density of $Ba(Fe_{1-x}M_x)_2As_2$ from optical experiments

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**Abstract**

The temperature dependence of the *ab*-plane optical reflectivity of $Ba(Fe_{0.92}Co_{0.08})_2As_2$ and $Ba(Fe_{0.95}Ni_{0.05})_2As_2$ single crystals is measured in a wide spectral range. Upon entering the superconducting regime, the reflectivity in both compounds increases considerably at low frequency, leading to a clear gap in the optical conductivity below 100 $cm^{-1}$. From the analysis of the complex conductivity spectra we obtain the penetration depth $\lambda(T) = (3500 \pm 350)$ Å for $Ba(Fe_{0.92}Co_{0.08})_2As_2$ and $(3000 \pm 300)$ Å for $Ba(Fe_{0.95}Ni_{0.05})_2As_2$. The calculated superfluid density $\rho_s$ of both compounds nicely fits Homes' scaling relation $\rho_s = (125 \pm 25)\sigma_{dc}T_c$.

*Key words:* Iron pnictides, superconductivity, optical properties
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$AFe_2As_2$ ($A$ = Ba, Sr, Eu) are $ThCr_2Si_2$-type ternary iron arsenides which exhibit a spin-density-wave (SDW) instability around 200 K. The development of the SDW gap was in detail investigated in $EuFe_2As_2$, for instance [1]. Additional charge carriers are provided by partial replace of Ba by K [2] or substitution of Fe by Co or Ni. Concomitantly the SDW transition shifts to lower temperatures and finally superconductivity sets in [3]. Here we present a comprehensive optical study on optimal electron-doped $Ba(Fe_{0.92}Co_{0.08})_2As_2$ ($T_c$=25 K) and $Ba(Fe_{0.95}Ni_{0.05})_2As_2$ ($T_c$=20 K) single crystals. The superconducting gap is clearly observed in reflectivity spectra for $T < T_c$. The spectral weight analysis on optical conductivity provides information on the penetration depth and the superfluid density.

Single crystals of $Ba(Fe_{0.92}Co_{0.08})_2As_2$ and $Ba(Fe_{0.95}Ni_{0.05})_2As_2$ were synthesized using self-flux method [3]. The platelets with a typical size of 2 mm × 2 mm × 0.1 mm have naturally flat and shiny surfaces. The resistivity and susceptibility evidence sharp superconducting transitions at 25 K and 20 K, indicating that samples are doped uniformly[4]. The temperature dependence of optical reflectivity was measured in a wide frequency range from 20 to 37 000 $cm^{-1}$ using a coherent-source spectrometer in the THz range, infrared Fourier transform spectrometers (Bruker IFS 66v/s and IFS 113v) and a Woollam spectroscopic ellipsometer extending up to the ultraviolet. The low-frequency extrapolation was done according to the dc conductivity measured on the same crystals by standard four-probe method. The optical conductivity was calculated from the reflectivity spectra using Kramers-Kronig analysis.

Fig. 1 shows the temperature dependent reflectivity and conductivity of $Ba(Fe_{1-x}M_x)_2As_2$. The $R(\omega)$ spectra show a good metallic behavior above $T_c$ as the reflectivity goes towards unity at low frequencies and increases by cooling. Upon entering the superconducting regime, the reflectivity starts to increase rapidly with a change in curvature below 70 $cm^{-1}$ and 60 $cm^{-1}$, respectively. This yields

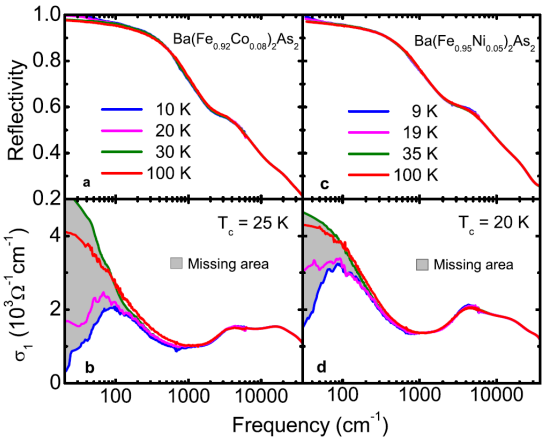


Fig. 1. (a,c) *ab*-plane optical reflectivity of $Ba(Fe_{0.92}Co_{0.08})_2As_2$ and $Ba(Fe_{0.95}Ni_{0.05})_2As_2$ measured over a wide frequency range shown for selected temperatures above and below the superconducting transition. (b,d) Frequency dependent conductivity obtained from the Kramers-Kronig analysis of the reflectivity. The missing spectral weights for both materials, between the conductivity curve just above the superconducting and the lowest measured temperature (30 K and 10 K, 35 K and 9 K respectively) are indicated by gray areas.

a gap-like feature in the $\sigma(\omega)$, indicating a formation of superconducting gap due to the pairing of electrons. According to the Ferrell-Glover-Tinkham sum rule, the removed spectral weight in $\sigma_1^{(s)}(\omega)$ compared to the normal-state $\sigma_1^{(n)}(\omega)$ is related to the formation of superconducting condensate: $A = \omega_{ps}^2/8 = c^2/8\lambda^2 = \int \left[\sigma_1^{(n)}(\omega) - \sigma_1^{(s)}(\omega)\right] \mathrm{d}\omega$, where the $\omega_{ps}$ is the plasma frequency of the Cooper pairs and $\lambda$ is the penetration depth [5]. Thus, from the missing area we directly estimate: $\lambda = (3500 \pm 350)$ Å for $Ba(Fe_{0.92}Co_{0.08})_2As_2$ and $(3000 \pm 300)$ Å for $Ba(Fe_{0.95}Ni_{0.05})_2As_2$. These values are in agreement with the results from measurements of the microwave surface-impedance, muon spin rotation and susceptibility. Another way to determine the penetration depth is from the imaginary part of the optical conductivity: $\lambda = c/\sqrt{4\pi\omega\sigma_2}$. Within the low-frequency limit, $\lambda$ calculated from imaginary part of the conductivity $\sigma_2(\omega)$ agrees well with the results from the spectral weight analysis.

The missing area is also a measure of the superfluid density $\rho_s = A/8$. Originally Uemura *et al.* [6] suggested a relation $\rho_s \propto T_c$ which works well in the case of underdoped cuprates. More recently, Homes *et al.* [7] extended the scaling relation by an additional term covering the optimal and overdoped cuprates as well: $\rho_s = (125 \pm 25)\sigma_{dc}T_c$, where the

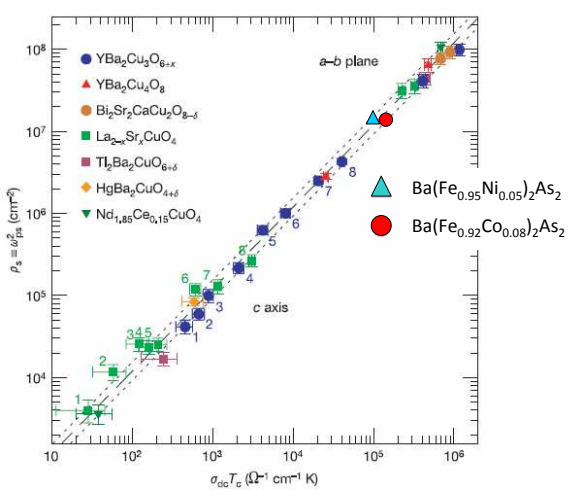


Fig. 2. Superfluid density $\rho_s$ versus $\sigma_{dc}T_c$ according to Homes *et al.* [7]. $Ba(Fe_{0.92}Co_{0.08})_2As_2$ and $Ba(Fe_{0.95}Ni_{0.05})_2As_2$ fall right on the scaling relation $\rho_s = (125 \pm 25)\sigma_{dc}T_c$ (lines) suggested for copper oxides.

$\sigma_{dc}$ is the value of dc conductivity just above $T_c$. Interesting this relation holds not only for the *ab*-plane but also for the measurements performed along the *c*-axis. In Fig. 2 we demonstrate that Homes' relation also holds very well for $Ba(Fe_{1-x}M_x)_2As_2$ family of materials. It is worth noting that the iron-pnictides are distinctively different to cuprates. While in iron pnictides the parent compounds are metallic, in cuprates they are insulating. Nevertheless they both fall right on this scaling relation. Studies over a larger doping range are needed to verify this scaling and draw further conclusions .

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