Optical and hidden transport properties of BaFe$_{1.91}$Ni$_{0.09}$As$_2$ film

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Abstract
Optical spectroscopy was used to study the electrodynamics and hidden transport properties of a BaFe$_{1.91}$Ni$_{0.09}$As$_2$ thin superconducting (SC) film. We analyzed the normal state data using a Drude–Lorentz model with two Drude components: one narrow (D$_1$) and another broad one (D$_2$). In the SC state, two gaps with $2\Delta_0^{(2)}/k_BT_c = 1.9–2.0$ and $2\Delta_0^{(1)}/k_BT_c = 4.0–4.3$ are formed from the narrow component D$_1$ while the broad component D$_2$ remains ungapped. The calculated total DC resistivity of the film and the low-temperature scattering rate for the narrow Drude component show a hidden Fermi-liquid behavior. The change of total electron–boson coupling ($\lambda_{ec}$) and representative energy ($\Omega_0$) in the normal state with respect to the SC state is typical of other iron-based materials as well as high-temperature superconducting (HTSC) cuprates.

Keywords: multiband superconductivity, iron-based superconductors, Eliashberg equations, non-phononic mechanism, transport properties, IR spectroscopy, ellipsometry

Supplementary material for this article is available online (Some figures may appear in colour only in the online journal)

1. Introduction
Iron-based superconductors are among the most studied superconducting (SC) compounds due to their high critical temperatures $T_c$, large upper critical field $H_{c2}$, type-II nature and relatively low anisotropy [1]. These characteristics make them promising candidates for various applications [2–4]. Among these materials, doped BaFe$_2$As$_2$ (Ba122) compounds attracted special attention due to a comparatively simple technology of growth at ambient pressure, good quality of available single crystals and the fact that superconductivity can be induced in many ways (i.e., by application of external pressure, by substitution of each atomic site or by combination of both routes), resulting in phase diagrams that are comparable [5]. Previous studies of iron-arsenic materials recognized their multiband nature with hole and electron pockets at the center and corners of the Brillouin zone [6, 7]. In this case, an analysis of optical data needs to include two different types of free-carrier contributions [8].

Many doped SC compounds of the Ba122-family can be grown as epitaxial thin films with decent quality [9]. However Fourier-transform infrared (FT-IR) spectroscopic studies...
of Ni-doped Ba122 epitaxial films have been reported only in [10]. The spectral range in this study was restricted to the interval from 50 to 7000 cm\(^{-1}\) and nothing was said on the values of SC gaps. Moreover, even for a bulk Ba(Fe, Ni)\(_2\)As\(_2\) data on the SC gap is scarce [11–16].

In our recent paper [17], we studied the optical properties of the BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film by THz spectroscopy within the range of 10–50 cm\(^{-1}\). The data was analyzed within a simple three-band Eliashberg model, where the mechanism of SC coupling is mediated by antiferromagnetic spin fluctuations, whose characteristic energy \(\Omega_0\) scales with \(T_c\) according to the empirical law \(\Omega_0 = 4.65k_B T_c\), and with a total electron–boson coupling strength \(\lambda_{tot} = 2.17\).

In the present paper, we studied the optical and hidden transport properties of the similar BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film by the combination of FT-IR spectroscopy and ellipsometry. Optical spectroscopy provides rich information on the bulk electronic properties of superconductors. It probes the energy, scattering and symmetry of the SC gaps and sum rules can be used to determine the SC condensate density. This data provides a deep insight into the pairing mechanisms in iron-based superconductors.

2. Experiment

The nearly optimum electron doped BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film with an approximate thickness of 120 ± 10 nm and an area of \(10 \times 10 \text{ mm}^2\) was grown by pulsed laser deposition (PLD) on polished (001) CaF\(_2\) substrate. More details on the sample preparation can be found in [18–20]. Electronic transport measurements of the film were performed using a standard four-probe configuration in a physical property measurement system (PPMS, Quantum Design). Figure 1 shows the dc in-plane resistivity of the BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film as a function of temperature (black open circles). The solid red curve represents the fit obtained with the Allen theory (see section 4 for more details). The inset shows the spectral function of the antiferromagnetic spin fluctuations in the normal state (see section 4).

![Figure 1. Temperature dependence of the resistivity for the BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film (black open circles). The solid red curve represents the fit obtained with the Allen theory (see section 4 for more details). The inset shows the spectral function of the antiferromagnetic spin fluctuations in the normal state (see section 4).](image)

Figure 2(a) shows the broad band reflectivity spectra \(R(\nu)\) of the BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film at various temperatures together with the fit based on the Drude–Lorentz analysis (see below). The reflectivity exhibits a metallic response for both frequency and temperature. The reflectivity curves almost overlap with each other above 100 cm\(^{-1}\) at temperatures of 5–100 K. Above 5700 cm\(^{-1}\) the difference between the spectra, including those taken at 100–300 K, is hardly discernible. However, a sudden upturn \(R(\nu)\) develops below \(T_c\) at frequencies as low as 60 cm\(^{-1}\) (7.4 meV). This is a strong indication for the formation of an SC energy gap due to the pairing of electrons. The decrease of \(R(\nu)\) becomes steep above 300 cm\(^{-1}\). In addition, our data contains two sharp features at \(\sim 94\) and \(\sim 260\) cm\(^{-1}\) which correspond to the contributions of phonons of the CaF\(_2\) substrate and symmetry-allowed \(ab\)-plane IR-active \(E_g\) phonons of the film [25].

We applied a full two-layer Drude–Lorentz modeling of the film/substrate system with a finite substrate thickness to the analysis of the experimental reflectivity together with the dielectric permittivity and optical conductivity (from the ellipsometry data) of the BaFe\(_{1.91}\)Ni\(_{0.09}\)As\(_2\) film. We used a two-Drude approach proposed earlier in [8] to study properties of
multiband iron pnictides. In this case, the optical conductivity in the normal state is modeled by two Drude components, one narrow (D1) and another broad one (D2), and by a set of Lorentz components representing the interband transitions. An alternative approach with the replacement of the broad Drude term by an overdamped Lorentzian is discussed in the supplement material [21]. The complex dielectric function is written as

\[
\tilde{\varepsilon}(\omega) = \varepsilon_{\infty} - \sum_{i=1,2} \frac{\omega_{Di}^2}{\omega^2 + i\gamma_i \omega} + \sum_j \frac{\omega_{j}^2}{\omega^2 - \omega_j^2 - i\gamma_j \omega},
\]

where \(\varepsilon_{\infty}\) is the background dielectric function, which comes from contribution of the high frequency absorption, \(D_1\) (\(D_2\)) stands for the narrow (broad) Drude component, \(\omega_{Di}\) is the Drude plasma frequency, \(\gamma_i\) is the (average) elastic scattering rate among free charge carriers, \(\omega_{j}/\gamma_j\), \(\omega_j\), and \(\gamma_j\) are the plasma frequency, the center frequency, and the width of the \(j\)th Lorentz component, respectively. The optical conductivity can be related to the dielectric function as

\[
\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega) = i\omega[\varepsilon_{\infty} - \tilde{\varepsilon}(\omega)]/4\pi.
\]

Below \(T_c\), the Drude term in the Drude–Lorentz model should be replaced by the Zimmermann term [26], which generalizes the standard BCS Mattis–Bardeen model [27, 28] to arbitrary \(T\) and \(\gamma\) values, with the inclusion of two additional parameters, the SC gap \(\Delta\) and the ratio \(T/T_c\).

In figure 2(b) we show the results of the modeling for the real part of the optical conductivity spectrum at various temperatures based on the Drude–Lorentz analysis. The noisy curves in the range of 4000–50 000 cm\(^{-1}\) are the optical conductivities calculated directly from the ellipsometry data. The CaF\(_2\) substrate has the strongest phonon peak at \(\sim 260\) cm\(^{-1}\). It was not included into the film model, which, nevertheless, provided a good quality of the fit. For the same reason, the phonon peak at \(\sim 94\) cm\(^{-1}\) was included only into the film model. In the normal state, the optical conductivity is decomposed into a narrow \(D_1\) and a broad \(D_2\) Drude terms as well as a set of Lorentzians representing interband transitions. The observation of narrow and broad terms in the two-Drude analysis is in agreement with other optical studies, and appears to be a general feature for most of the iron-based materials having multiband structure [8]. As temperature decreases, the \(D_1\) component increases and gets narrower while the \(D_2\) component as well as Lorentz contributions remain virtually unchanged.

Upon passing the SC transition a gaplike structure is formed in the narrow Drude term. Assuming two isotropic SC gaps both opening simultaneously below \(T_c\), we obtain a better description of the low-frequency optical conductivity with \(2\Delta_0^{(1)} = 56–60\) cm\(^{-1}\) (6.9–7.4 meV) and \(2\Delta_0^{(2)} = 26–27\) cm\(^{-1}\) (3.2–3.4 meV). Forty five percent of the initial conductivity is due to the larger gap and fifty five percent of the conductivity is accounted for by the smaller one. The gap values obtained from our study are \(2\Delta_0^{(1)}/k_B T_c = 4.0–4.3\) and \(2\Delta_0^{(2)}/k_B T_c = 1.9–2.0\), respectively. These values are consistent with the SC gaps of BaFe\(_{1.9}\)Ni\(_{0.9}\)As\(_2\) single crystals determined from specific heat measurements as well as directly by intrinsic multiple Andreev reflections effect (IMARE) spectroscopy [15, 16]. A three-band Eliashberg model used for the analysis of our previous THz spectroscopy data for the similar BaFe\(_{1.9}\)Ni\(_{0.9}\)As\(_2\) film \((T_c = 19.6\) K) [17] produces quite different values of the SC gaps, \(2\Delta_1/k_B T_c = 5.1\), \(2\Delta_2/k_B T_c = 3.3\), and \(2\Delta_2/k_B T_c = 7.0\). Such a difference can be related to the slightly different \(T_c\) of our films as well as the coupling constants for Ba(Fe, Co)\(_2\)As\(_2\) used in previous calculations.

It is seen from figure 2(b) that the broad Drude term is not gapped at least in the range of our measurements. For the case that the coherent transport in the normal state arises mainly from the electron pocket, the observed two energy scales for the SC energy gaps might be due to a single anisotropic s-wave gap at the electron pocket (see the results for Co–Ba122 having very similar electronic structure [29]). This picture is consistent with a s\(_k\) symmetry of the order parameter.

It should be noted that the use of other models, e.g., with one gap either in the \(D_1\) or \(D_2\) term or two gaps belonging to the different terms or to the \(D_2\) term does not provide an adequate description of the experimental data. However, the replacement of the broad Drude term by an overdamped Lorentzian also provides a good fit to the reflectivity spectra of the BaFe\(_{1.9}\)Ni\(_{0.9}\)As\(_2\) film in the normal state (see figure S4(a) in the supplemental material [21]). In the SC
state, a simple single-band theory fails to describe the low-frequency reflectivity spectrum (dash-dot curve in the inset of figure S4(a)). The consideration of two SC gaps both opening in a single band or in the different bands having similar parameters provides the best fit with the gap magnitudes $2\Delta_0^{(1)} = 51.5 \text{ cm}^{-1}$ and $2\Delta_0^{(2)} = 23.6 \text{ cm}^{-1}$ (figure S4(b) in the supplemental material [21]). These values are very close to those obtained above with a two-Drude model, which confirms the reliability of these results.

To see the role of impurities in the mechanism of superconductivity, it is instructive to compare the magnitudes of SC gaps obtained in this study for BaFe$_{1+\delta}$Ni$_{0.05}$As$_2$ with those extracted from IR for other electron doped Ba122 systems such as Co–Ba122 and Pt–Ba122 with the similar levels of doping. Since Co donates only one additional 3d electron compared to Fe, while Ni has two 3d electrons more, one should use the composition close to BaFe$_{1+\delta}$Co$_{0.05}$As$_2$ for comparison (table 1). In the case of BaFe$_{1+\delta}$Pt$_{0.1}$As$_2$, optical conductivity data is consistent with three nodeless energy gaps in the SC state [30]. From table 1 we may conclude that the same quantity of similar dopant produces analogous effect on the $T_c$ and SC gap magnitudes in electron-doped Ba122 ferropnictides. This means that the mechanism of superconductivity in these materials is robust against the change of dopants with similar properties and not prone to fine tuning.

In figure 3 are shown the temperature dependences of the fitting parameters of two Drude modes for the BaFe$_{1+\delta}$Ni$_{0.05}$As$_2$ film in the normal state. The parameters are the plasma frequency ($\omega_{D,p}$), the static scattering rate ($\gamma$), the DC conductivity ($\sigma_{DC}$), and the DC resistivity $\rho$ of the two Drude modes. One can see that $\omega_{D1,p}$, $\gamma_{D2}$, and $\rho_{D2}$ show some temperature dependences as opposed to their variability found for Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystals [32], Ni–Ba122 single crystals [33], and BaFe$_{1+\delta}$Ni$_{0.1}$As$_2$ film [10]. However, at least below 200 K these parameters are nearly temperature independent. Moreover, the Drude plasma frequency $\omega_{D2} = \sqrt{4\pi ne^2/m^*}$ ($n$ is the carrier concentration, $m^*$ is an effective mass) deduced from the one Drude-one Lorentzian model is also temperature independent as is evident from figure S3(a) of the supplemental material [21]. This indicates that the band structure and $n/m^*$ of BaFe$_{1+\delta}$Ni$_{0.05}$As$_2$ do not change noticeable with temperature. On the contrary, the scattering rate data for the narrow Drude contribution indeed demonstrates a quadratic dependence at low temperatures as is evident from figure 3(b) with the quadratic function shown by the dashed line. The total DC resistivity estimated from the optical data can be calculated using the expression $1/\rho_{D1+D2} = 1/\rho_{D1} + 1/\rho_{D2}$. It shows a $T^2$ behavior as can be seen from figure 3(d). Such a behavior is also characteristic for $\gamma_{D0}(T)$ and $\rho(T)$ obtained within a one Drude-one Lorentzian model described in supplemental material [21] (see figures S3(b) and (d)). This is a further proof for the validity of the obtained results. A quadratic temperature dependence is expected for electron–electron scattering which is supposed to be dominant for correlated electron systems at low temperatures and subject to Landau’s theory of a Fermi liquid [34, 35]. Such a behavior was previously observed for BaFe$_{1+\delta}$Ni$_{0.1}$As$_2$ PLD film [10] as well as for BaFe$_{1+\delta}$Ni$_{0.1}$As$_2$ and BaFe$_{1+\delta}$Co$_{0.1}$As$_2$ single crystals [33, 36], while for hole-doped Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ a $T$-linear behavior was found [32]. This indicates that the electron- and hole-doped samples show different hidden $D_1$ transport properties.

The total DC resistivity estimated from the optical data shows a similar temperature dependence but some difference in magnitude as compared with the transport resistivity data. We think that the difference might originate from the uncertainties of the resistivity data obtained by two different measurement methods. In the following, we want to discuss the resistivity in more detail.

### 4. Model for the resistivity in a multiband metal

The resistivity in a multiband case can then be obtained by extending the single band case [37, 38] and considering the

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**Table 1. Some SC parameters for electron-doped Ba122 ferropnictides with the similar levels of doping.**

| Compound       | $T_c$, K | $\Delta_c$, meV | $\Delta_s$, meV | $2\Delta_c/\kappa_B T_c$ | $2\Delta_s/\kappa_B T_c$ | Method          | Reference   |
|----------------|----------|-----------------|-----------------|--------------------------|--------------------------|-----------------|-------------|
| BaFe$_{1+\delta}$Ni$_{0.05}$As$_2$ | 20       | 1.6–1.7         | 3.45–3.7        | 1.9–2.0                  | 4.0–4.3                  | Optical conductivity, this study | —           |
| BaFe$_{1+\delta}$Co$_{0.05}$As$_2$ | 20       | 1.85            | 3.95            | 2.15                     | 4.6                      | Optical conductivity [31]       |             |
| BaFe$_{1+\delta}$Pt$_{0.1}$As$_2$  | 23       | 1.95            | 3.6, 5.4        | 1.97                     | 3.63, 5.44               | Optical conductivity [30]       |             |

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**Figure 3.** The fitting parameters $\omega_{D0,i}$ (a) and $\gamma_{D0,i}$ (b) of two Drude modes $D_i (i = 1, 2)$ of the BaFe$_{1+\delta}$Ni$_{0.05}$As$_2$ film. We also show the calculated DC conductivities $\sigma_{DC}(T)$ (c) and DC resistivity $\rho(T)$ (d) including the total resistivity as functions of temperature. The dashed lines are $T^2$ fits to the scattering rate for the narrow Drude component and to the total DC resistivity.
The contribution of all the different channels:

$$\frac{1}{\rho(T)} = \frac{\varepsilon_0(h\omega_p)^2}{h} \sum_{i=1}^{N} \left( \omega_{pi}/\omega_p \right)^2 \gamma_i + W(T),$$  \(1\)

where \(N\) is the total number of the different carriers considered, \(\omega_{pi}\) is the bare plasma frequency of the i-band, \(\omega_p\) is the total bare plasma frequency and

$$W(T) = 4\pi k_b T \int_0^{\infty} d\Omega \left[ \frac{h\Omega/2k_b T}{\sinh \left( h\Omega/2k_b T \right)} \right]^2 \frac{\Omega_i^2 F_{\alpha}^0(\Omega)}{\Omega},$$  \(2\)

with \(\gamma_i = \sum_{j=1}^{N} \Gamma_{ij} + \Gamma_{ji}'\) is the sum of the inter- and intra-band non magnetic and magnetic impurity scattering rates present in the Eliashberg equations and

$$\alpha_{ij}^2 F_{\alpha}^0(\Omega) = \sum_{\nu=1}^{N} \alpha_{ij\nu} F_{\nu}(\Omega),$$  \(3\)

where \(\alpha_{ij}^2 F_{\alpha}^0(\Omega)\) are the transport spectral functions related to the Eliashberg functions [37].

We can define a normalized spectral functions \(\alpha_{ij}^2 F_{\alpha}^0(\Omega)\) that has an electron-boson coupling constant \(\lambda = 2\int_0^{+\infty} \frac{\Omega_i F_{\alpha}^0(\Omega)}{\Omega} d\Omega\) equal to 1 which results in \(\alpha_{ij}^2 F_{\alpha}^0(\Omega) = \lambda_{ij} \Omega_{ij}^2 F_{\alpha}^0(\Omega)\).

To write the reciprocal resistivity as a sum of \(N\) different contributions is an approximation that was discussed already in the past in reference [39]. This approximation works, if the material is not in a strong disorder regime. This means in particular for the temperature range of interest the resistivity has not yet entered a strong disorder regime. This means in particular for the temperature range of interest the resistivity has not yet entered a strong disorder regime. Therefore, we group all spectral functions to be equal and they differ just for a scaling factor, the coupling constant (this is a very good approximation, especially if the coupling is mediated mainly by spin fluctuations), then \(\alpha_{ij}^2 F_{\alpha}^0(\Omega) = \lambda_{ij} \Omega_{ij}^2 F_{\alpha}^0(\Omega)\) and \(\lambda_{ij} = \sum_{\nu=1}^{N} \lambda_{\nu ij}\). The specific shape of the spectral function for the antiferromagnetic spin fluctuation in the normal state is standard [41]. The shape and position of the peak are the same for the spectral functions in all bands. They are just rescaled for having different \(\lambda_{ij}\) (electron–boson coupling constant).

The Fermi surface consists of several sheets, therefore a multi-band model is in principle required to explain SC and normal state properties. In order to study the electrical resistivity, we grouped the hole and the electron bands, i.e. a model containing only two different kind of carriers is used. Considering the fact that the electron–phonon coupling in all iron-based superconductors is weak [42], it is logic to consider another mechanism, which contributes to the transport properties. Knowing the basic SC properties of iron pnictides, antiferromagnetic spin fluctuations are the best candidates to play the role of the principal actor also in the normal state.

The transport spectral functions are similar to the standard Eliashberg functions [37], the only difference between SC and normal state is the behavior for \(\Omega \rightarrow 0\), where the transport function behaves like \(\Omega^3\) instead of \(\Omega\). Therefore, the condition \(\alpha_{ij}^2 F_{\alpha}^0(\Omega) \ll \Omega^3\) should be imposed in the range \(0 < \Omega < 10\omega_p\), with \(10\omega_p \approx 10\Omega_0/10\) where \(\Omega_0\) is the representative bosonic energy [37]. Then \(\alpha_{ij}^2 F_{\alpha}^0(\Omega) = b_i \Omega^3/\Omega_0 - \Omega_0 + c_i \Omega^2 (\Omega - \Omega_0)\) and the constants \(b_i\) and \(c_i\) have been fixed by requiring the continuity in \(\Omega_0\gamma\) and the normalization. This function is shown in the inset of figure 1.

In order to describe the coupling with spin fluctuations, we observe the \(\alpha_{ij}^2 F_{\alpha}^0(\Omega)\) the functional form of the theoretical antiferromagnetic spin fluctuations function in the normal state [43] that reproduces the experimental data concerning the normal state dynamical spin susceptibility [44]

$$\alpha_{ij}^2 F_{\alpha}^0(\Omega) \propto \frac{\Omega_0 \Omega}{\Omega^2 + \Omega_0^2} \vartheta(\Omega - \Omega_0),$$  \(4\)

where \(\Omega_0\) is a cut-off energy (in these calculations \(\Omega_0 = 1\) eV) and \(\Omega_0\) is the energy of the peak.

As mentioned above, the electronic structure in these compounds consists of hole and electron pockets. In order to keep the number of free parameters as low as possible and taking into account that just one carrier is not enough, we consider a model containing only two different kinds of carriers. Within this model the electron–boson coupling constants \(\lambda_{1\nu}\) and \(\lambda_{2\nu}\), the impurities contents \(\gamma_1\) and \(\gamma_2\), the plasma energies \(\omega_{p,1}\) and \(\omega_{p,2}\), the representative energy \(\Omega_0\) of the transport electron–boson spectral functions and the energy \(\Omega_0\) are free parameters. In the Co doped case, ARPES and de Haas-van Alphen data suggest that the transport is drawn mainly by the electronic bands and that the hole bands are characterized by a weaker mobility [31]. This means that within our model the impurities are mostly concentrated in the hole band (indicated by the index 2), i.e. \(\gamma_2 \gg \gamma_1\), while the transport coupling is much higher in the electron band (indicated by the index 1); then, at least as a first approximation, \(\lambda_{1\nu}\) can be fixed to be zero. In this way one contribution results to be temperature independent and the other changes the slope of the resistivity with the temperature. The values of \(\gamma_1\) and \(\gamma_2\) are connected with the experimental value of \(\rho(T = 0) = 218 \mu\Omega \cdot \text{cm}\) so just one is free. We take the total plasma energy \(\omega_p = 2101\) meV from our optical measurements as \(\omega_{p,1} = 1118\) meV (\(\omega_{p,2} = 1779\) meV) and \(\gamma_2 = 262\) meV (\(\gamma_1 = 50\) meV), all at \(T = 20\) K, so at the end we have 3 free parameters. We find \(\lambda_{1\nu} = 1.59\), \(\Omega_0 = 80\) meV and we choose, as in the Co doped case [41], \(\Omega_0 = \omega_p/2 > \omega_p/10\). The value of parameters found are similar to the Co doped case and also the total coupling \(\lambda_{ij} = 0.51\) is small [41]. The final result is good as it is shown in figure 1 (red line).

We note that there is a big increase for the typical energy \(\Omega_0\) of the electron–boson coupling from the SC to the normal state in agreement with inelastic neutron scattering experimental data [44]. Moreover, the electron–boson spectral density extracted using Eliashberg equations from optical conductivity of Co doped BaFe$_2$As$_2$ [45] shows exactly the same behav—
ior and is another evidence that in iron-based superconductors spin fluctuations strongly couple to the charge carriers and mediate superconductivity. The fit of the dc resistivity shows also a significant decrease of the coupling constant $\lambda_{ab}$ in relation to the SC state ($\lambda_{ab0}$). It was shown for simple metals that $\lambda_{ab} \lesssim \lambda_{ab0}$ while in strongly correlated materials like HTSC cuprates holds $\lambda_{ab} \ll \lambda_{ab0}$ [46]. This behavior is also typical of other iron-based materials [40, 41] and may have its origin in strong electronic correlations [46]. This indicates that for $ab\text{i}n\text{itio}$ calculations of the physical properties of these materials electronic correlations cannot be neglected.

5. Conclusion

In conclusion, we studied the optical and hidden transport properties of the nearly optimum doped BaFe$_{1.91}$Ni$_{0.99}$As$_2$ SC film. A two-Drude model was found to describe successfully the optical properties of the film studied. In the SC state two gaps with $2\Delta_0^{(1)}/k_BT_c = 1.9$–$2.0$ and $2\Delta_0^{(2)}/k_BT_c = 4.0$–$4.3$ are formed from the narrow Drude component $D_1$ while the broad component $D_2$ remains ungapped. An alternative one Drude-one Lorentzian model gives almost similar values for the SC gaps but admits their opening in different bands having similar parameters. The temperature dependences of the model parameters in the normal state are examined within both models. A hidden Fermi-liquid behavior found earlier for optimally doped Ba(Fe, Ni)$_2$As$_2$ PLD film [10] and single crystal [33] is confirmed. From the resistivity measurement as a function of temperature we realize that the electron–boson coupling constant is strongly reduced and the representative boson energy is strongly increased as it happens with the other iron-based materials [40, 41] and HTSC cuprates [46]. The similar behavior probably results from the fact that the mechanism responsible for superconductivity is, perhaps, similar for HTSC cuprates and iron-based materials.

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