*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-5.046 (2004)*

Ionization Balance and Electrical Conductivity of Nonideal Metal Plasmas

Deok-Kyu Kim[1] and Inho Kim[2]

Agency for Defense Development, P.O.Box 35-5, Yuseong, Daejeon, 305-600, Korea
1. E-mail address: dkyukim@add.re.kr
2. E-mail address: kiminho@add.re.kr

Abstract

We have implemented a practical approach to calculate the ionization balances and electrical conductivities in warm dense metal plasmas. The corrected form of ionization potential for nonideal plasma has been derived with the Coulomb coupling effect taken into account utilizing the excess free energy models currently available. The ionization balances in metal plasmas are computed in the parameter range of temperature of 10 000-30 000 K and density up to 10 g/cm^3 and the results are shown to effectively demonstrate the pressure-induced ionization near solid densities. The electrical conductivities of partially ionized metal plasmas are then evaluated based on a linear mixture rule that takes account of both the electron-ion and electron-neutral collisions. The calculated conductivity values appear in reasonable agreement with measured data from recent wire-explosion experiments accounting for the metal-insulator transition.

I. Introduction

In warm dense plasmas which are typically found in experiments of metal wire explosion [1,2], Coulomb interactions between charged particles become important as the Coulomb energy grows to be comparable to the thermal energy [3]. Strong Coulomb couplings have critical effects on the ionization balance in equilibrium state, generally leading to a significantly increased degree of ionization due to the reduced ionization potentials of constituent atoms and ions. Plasmas in this condition are referred to as nonideal and well characterized by the Coulomb coupling constant Γ which is defined as the ratio of the average Coulomb energy to the average thermal energy. Recently, plasma transport properties in nonideal regime are of high interest, particularly, in concern with the physics relevant to the metal-insulator transitions occurring near solid densities [1].

Here, we introduce a generalized formulation of the corrected ionization potential taking account of the strong Coulomb coupling effect to compute the ionization balances in warm dense plasmas of various metal elements: aluminum, iron, nickel, and copper. The final form of corrected potential formula is given by incorporating a number of excess free energy models available. After determining the ionization balances in dense metal plasmas using the corrected potential formula, we calculate the electrical conductivities in partially ionized regime following a linear mixture rule. The calculated results are presented in comparison with measurements from recent metal wire-explosion experiments to account for the metal-insulator transition.

II. Ionization balance and electrical conductivity in nonideal plasmas

Formulation of the potential correction term, which lowers the ionization potential in strongly coupled plasmas, is derived based on the minimum-free-energy principle [3]. The total excess free energy arising from Coulomb couplings between charged particles can be expressed as a linear combination of three partial terms that are associated with the electron-electron, ion-ion, and electron-ion interactions, respectively. Each free energy term has been given by other authors as a function of dimensionless key parameters characterizing nonideal plasmas: our work employs the analytic expression f_C^{ee} proposed by Tanaka, Mitake, and Ichimaru [4] for electron-electron interactions and the accurate fitting formulas f_C^{ii} and f_C^{ei} by Charbrier and Potekhin [5] for ion-ion and electron-ion interactions, respectively. Incorporating these excess free energy models in the corrected ionization potential formula, we obtain its final form as presented in Ref. [6]. Now the whole set of ionization balance equations with corrected ionization potentials are solved to determine the compositions of electrons and ions in a large temperature-density domain covering the strongly coupled plasma regime near solid densities.

We then evaluate the electrical conductivities of partially ionized plasmas by including electron collisions with both ions and neutral atoms according to a linear mixture rule, which simply adds the electron-ion and electron-atom collision frequencies to give the total frequency. The electron-ion collision frequency is readily obtained from a simplified formula that has been devised to describe dense plasmas [7]. To compute the electron-atom collision frequency, we use a fitted formula of the average momentum transfer cross section given by Desjarlais [8].

III. Computed results

The compositions of electrons, ions, and neutral atoms in aluminum plasma, which have been determined by solving the ionization balance equations with the Coulomb coupling effect included, are shown in Fig. 1 exhibiting a rapid growth of ionization degree near solid densities, $\rho \sim 1$ g/cm^3, in a warm temperature condition of $T = 14\,000$ K, which we consider to successfully demonstrate the pressure-ionization. The overall composition profiles of the other metal plasmas also appear with similar patterns.

Figure 2 shows the calculated electrical conductivities in metal plasmas of (a) aluminum, (b) iron, (c) nickel, and (d) copper at T = 14 000 K in comparison with data from wire-explosion experiments measured by DeSilva and Katsouros [1] and Benage, Shanahan, and Murillo [2] as well as with the classical Spitzer-Härm model [9]. At this warm temperature, the electrical conductivities tend to decrease with the plasma density in the range $\rho > 10^{-3}$ g/cm^3 and then reach its minimum value at $\rho \sim 0.1$ g/cm^3 due to the decreasing ionization degree at high densities. As the density increases further beyond this level, sudden increases of electrical conductivity occur with the rapidly rising electron population caused by pressure-ionization as depicted in Fig. 1. The calculated results seem to reasonably agree with the experimental measurements accounting for the metal-insulator transitions encountered at extreme pressures.

IV. Conclusions

We implemented a mathematical formulation for corrected ionization potential to take account of the Coulomb coupling effect in nonideal plasmas and computed the ionization balances and electrical conductivities of dense metal plasmas. The calculated conductivities appear to well reproduce the experimental measurements in a metal-insulator transition regime.

References

[1] A. W. DeSilva and J. D. Katsouros, Phys. Rev. E 57, 5945 (1998).
[2] J. F. Benage, W. R. Shanahan, and M. S. Murillo, Phys. Rev. Lett. 83, 2953 (1999).
[3] S. Ichimaru, *Statistical Plasma Physics Vol. II: Condensed Plasmas* (Addison-Wesley, New York, 1994).
[4] S. Tanaka, S. Mitake, and S. Ichimaru, Phys. Rev. A 32, 1896 (1985).
[5] G. Chabrier and A. Y. Potekhin, Phys. Rev. E 58, 4941 (1998).
[6] D.-K. Kim and I. Kim, Phys. Rev. E 68, 056410 (2003).
[7] R. J. Zollweg and R. W. Liebermann, J. Appl. Phys. 62, 3621 (1987).
[8] M. P. Desjarlais, Contrib. Plasma Phys. 41, 267 (2001).
[9] L. Spitzer, Jr., *Physics of Fully Ionized Gases, 2nd ed.* (Interscience, New York, 1962).

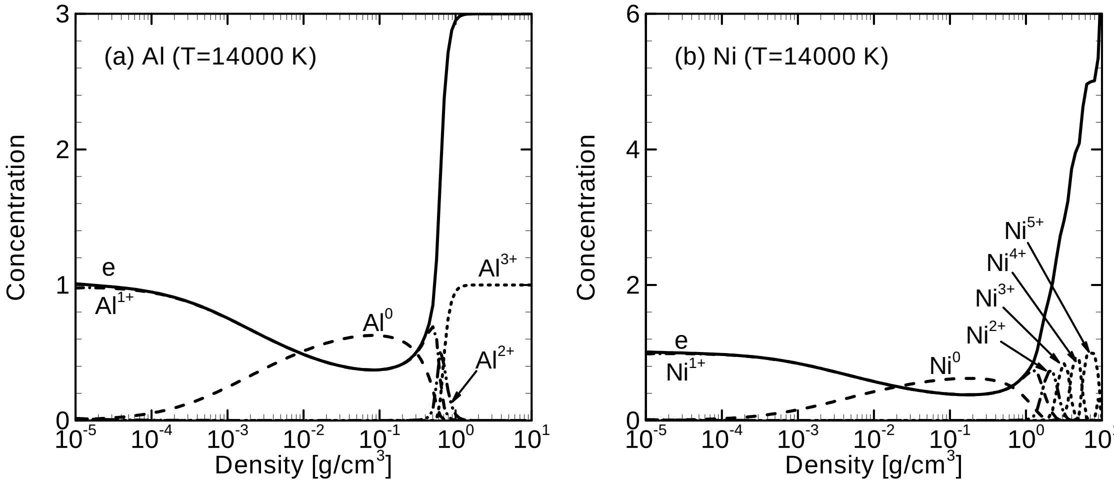

Fig. 1 Compositions of electrons, ions, and neutral atoms in warm metal plasmas computed by the present model as a function of density at T = 14 000 K: (a) aluminum and (b) nickel.

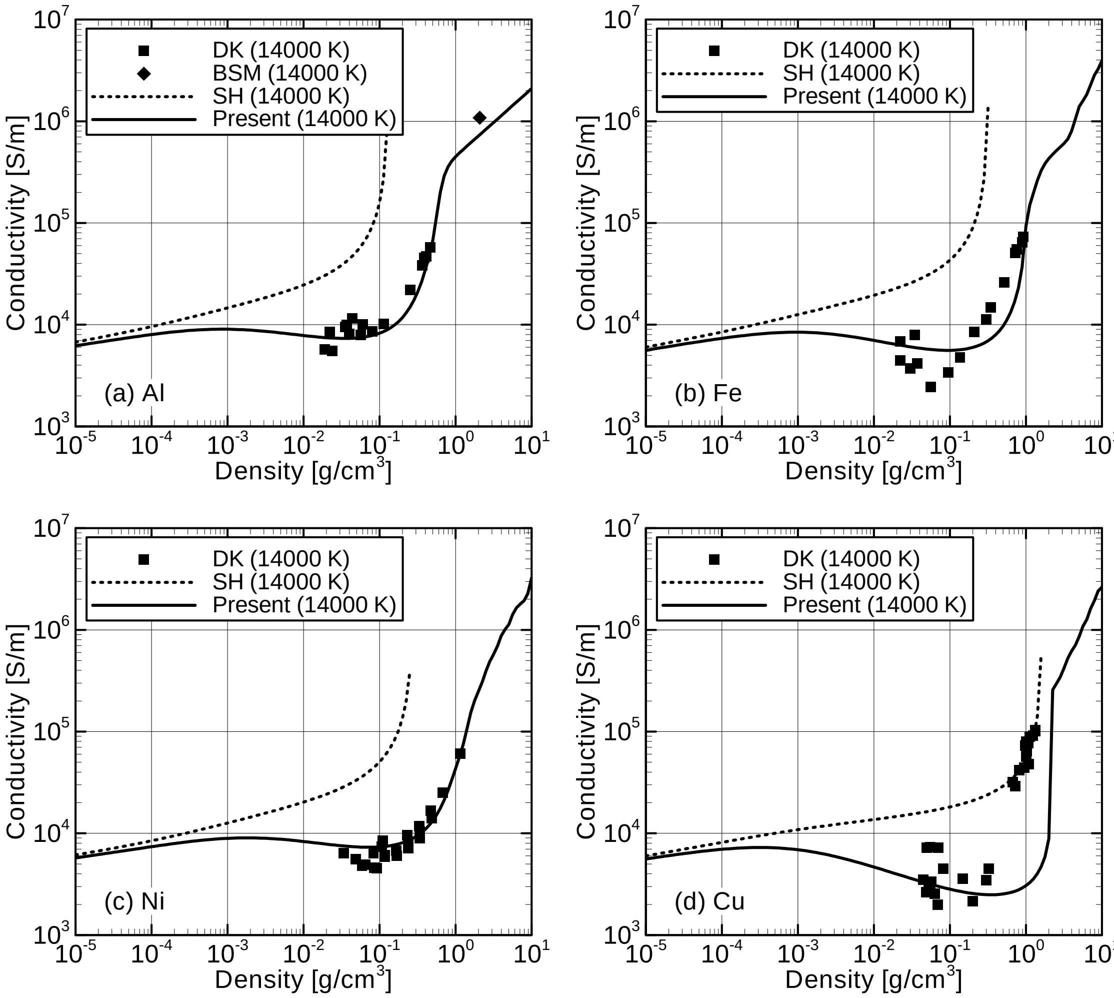

Fig. 2 Electrical conductivities of warm metal plasmas computed by the present model for (a) aluminum, (b) iron, (c) nickel, and (d) copper in comparison with the Spitzer-Härm (SH) model and the experimental data measured by DeSilva and Karsouros (DK) and Benage, Shanahan, and Murillo (BSM) at T = 14 000 K.