Electrical transport in amorphous semiconducting AlMgB14 films

Y. Tian  
Iowa State University

G. Li  
Iowa State University

Joseph Shinar  
Iowa State University, shinar@ameslab.gov

N. L. Wang  
Iowa State University

Bruce A. Cook  
Iowa State University

Follow this and additional works at: http://lib.dr.iastate.edu/mse_pubs

Part of the Electrical and Computer Engineering Commons, Engineering Physics Commons, and the Metallurgy Commons

The complete bibliographic information for this item can be found at http://lib.dr.iastate.edu/mse_pubs/4. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
Electrical transport in amorphous semiconducting AlMgB14 films

Abstract
The electrical transport properties of semiconducting AlMgB14 films deposited at room temperature and 573K are reported in this letter. The as-deposited films are amorphous, and they exhibit high n-type electrical conductivity, which is believed to stem from the conduction electrons donated by Al, Mg, and/or Fe impurities in these films. The film deposited at 573K is less conductive than the room-temperature-deposited film. This is attributed to the nature of donor or trap states in the band gap related to the different deposition temperatures.

Keywords
Ames Laboratory, Physics and Astronomy, Electrical and Computer Engineering

Disciplines
Electrical and Computer Engineering | Engineering Physics | Materials Science and Engineering | Metallurgy | Physics

Comments

Rights
Copyright 2004 American Institute of Physics. This article may be downloaded for personal use only. Any other use requires prior permission of the author and the American Institute of Physics.

Authors
Y. Tian, G. Li, Joseph Shinar, N. L. Wang, Bruce A. Cook, James W. Anderegg, Alan P. Constant, Alan Mark Russell, and J. E. Snyder

This article is available at Iowa State University Digital Repository: http://lib.dr.iastate.edu/mse_pubs/4
Electrical transport in amorphous semiconducting AlMgB₁₄ films

Y. Tian
Department of Materials Science and Engineering, Iowa State University, Ames, Iowa 50011

G. Li and J. Shinar
Ames Laboratory-USDOE and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011

N. L. Wang
Department of Electrical and Computer Engineering, Iowa State University, Ames, Iowa 50011

B. A. Cook and J. W. Anderegg
Ames Laboratory, United States Department of Energy, Ames, Iowa 50011

A. P. Constant, A. M. Russell, and J. E. Snyder
Department of Materials Science and Engineering, Iowa State University, Ames, Iowa 50011

(Received 11 December 2003; accepted 15 June 2004)

The electrical transport properties of semiconducting AlMgB₁₄ films deposited at room temperature and 573 K are reported in this letter. The as-deposited films are amorphous, and they exhibit high n-type electrical conductivity, which is believed to stem from the conduction electrons donated by Al, Mg, and/or Fe impurities in these films. The film deposited at 573 K is less conductive than the room-temperature-deposited film. This is attributed to the nature of donor or trap states in the band gap related to the different deposition temperatures. © 2004 American Institute of Physics.

Boron-rich boride films are refractory semiconductors, which have been the subject of intense investigation in recent years due to their attractive properties, including high hardness (>30 GPa), high melting point (>2000 °C), low density, extremely low γ-radiation absorption, chemical inertness, and thermal stability at high temperatures. These materials may be useful in electronic devices operating in a wide variety of extreme or harsh environments (mechanically abrasive, radiative, corrosive, and/or high temperature). Implementation of these materials will require a thorough understanding of their electrical properties, which are profoundly influenced by their composition, microstructure, and deposition methods. Considerable research has focused on the electrical transport mechanism, dielectric properties, doping behavior, and device performance of boron compounds with C, N, and O, such as BₓC/CoₓC, BₓN (x > 1) and boron suboxide (BₓOₓ, x > 1). Recently, the ternary boride compound AlMgB₁₄ has attracted attention due to its interesting mechanical properties, however, no studies have been reported on the electrical properties of AlMgB₁₄ thin films. This letter discusses the effect of deposition temperature on the electrical properties of AlMgB₁₄ films. More specifically, the study shows that AlMgB₁₄ films are unusual in two regards when compared to other boron-rich boride films: They have an unusually low resistivity, and the charge carriers are predominantly n type.

The AlMgB₁₄ films were grown by pulsed laser deposition (PLD) from a hot-pressed Alₓ₀.₉₅Si₀.₀₅MgB₁₄ target on thermally oxidized Si (100) and Corning 7059 glass at room temperature and 573 K, respectively. The ambient pressure was maintained below 6 × 10⁻⁷ Torr. The composition of AlMgB₁₄ films was determined by x-ray photoelectron spectroscopy (XPS). The electrical resistivity of AlMgB₁₄ films was measured at room temperature using the four-point probe and van der Pauw method. In addition, van der Pauw Hall measurements were carried out on AlMgB₁₄ films to determine the carrier type, carrier concentration, and Hall mobility. The contacts were formed with Ag paint, and exhibited ohmic characteristics after a 5 h of baking at 100 °C, as indicated by room temperature current–voltage (I–V) measurements. A hot probe method was also employed to determine the carrier type in AlMgB₁₄ films. The dark current I, at a constant voltage of 5 V, was recorded as a function of temperature T from 300 K to 453 K, with Al stripes made by thermal evaporation as contacts. The optical absorption spectra of the films grown on Corning 7059 glass were measured by a Perkin–Elmer ultraviolet-visible-near-infrared spectrophotometer. The optical band gaps were determined by fitting the optical absorption spectra to the Tauc equation.

PLD is considered a viable means of transferring target stoichiometry to thin films, and this has been confirmed by XPS analysis in the case of AlMgB₁₄ films. However, XPS measurements also indicated significant amounts of O and Fe in the films, which was discussed elsewhere. XPS also indicated that there is no appreciable difference in composition between room-temperature- and 573 K-deposited AlMgB₁₄ films. The microstructure of AlMgB₁₄ films, which was examined by transmission electron microscopy, remains amorphous regardless of substrate temperature, and no evidence of conducting inhomogeneities or crystalline domains was observed.

The electrical properties of the AlMgB₁₄ films are summarized in Table I. Compared with the electrical resistivity of other boron-rich boride films, which typically cover a wide range of values from ~10³ to 10⁹ Ω cm, the electrical resistivity of room-temperature- and 573 K-deposited AlMgB₁₄ films is approximately three to eight orders of magnitude lower.
magnitude lower, approaching that of single-crystal boron carbide. Such low resistivity is particularly noteworthy since the films are entirely amorphous. Furthermore, the charge carriers in these AlMgB\textsubscript{14} films are dominated by electrons, as opposed to the holes which prevail in most boron-rich boride materials.

The low electrical resistivity observed in AlMgB\textsubscript{14} films is clearly a consequence of a high carrier concentration combined with moderate carrier mobility. In general, the electronic structure of all boron-rich boride materials is essentially determined by the B\textsubscript{12} icosahedra. The valence band (VB) of these materials typically consists of an upper split-off subband VB\textsubscript{1}, which is generated by the Jahn-Teller distortion of the B\textsubscript{12} icosahedra, and a lower subband VB\textsubscript{2}.\textsuperscript{14} VB\textsubscript{1} is partially occupied by electrons in low-density localized states; these electrons are thermally excited from VB\textsubscript{2} with free holes left behind, thus VB\textsubscript{1} acts like an intrinsic acceptor level in nature. Accordingly, two transport mechanisms are operative: Electron hopping at the Fermi level in VB\textsubscript{1} and free hole conduction in the extended states of VB\textsubscript{2}.\textsuperscript{15} Moreover, strong electron–phonon coupling in B\textsubscript{12} icosahedra leads to the formation of six intrinsic high-density trap levels within the band gap.\textsuperscript{15} For most boron-rich boride materials, electrical transport by holes predominates because the excited electrons can be easily captured in the trap states. Nevertheless, Lewis \textit{et al.}\textsuperscript{16} reported an extremely high \textit{n}-type carrier concentration (~$10^{21} \text{cm}^{-3}$) and low carrier mobility (~$0.133 \text{cm}^{2}/\text{V s}$) associated with fine-grained, hot-pressed AlMgB\textsubscript{14}, which they attributed to electron hopping mechanism.\textsuperscript{16}

Neither electron hopping nor band conduction by holes can reasonably explain the unique transport behavior of the AlMgB\textsubscript{14} films. The significantly enhanced \textit{n}-type carrier mobility observed in the films (4.86 and 6.89 cm\textsuperscript{2}/V s) suggests that it is the electrons, which are excited beyond the mobility edge into extended states of the conduction band,\textsuperscript{17} that play a key role in the transport process of AlMgB\textsubscript{14} films. Moreover, the high carrier concentration ($10^{16}–10^{17} \text{cm}^{-3}$) suggests that these electrons are provided by metallic dopants in AlMgB\textsubscript{14} films, because pure boron films typically have far lower \textit{p}-type carrier concentrations (~$10^{13} \text{cm}^{-3}$).\textsuperscript{18} There are two pathways to introduce dopants into the boron-rich boride materials: Substitution and network modification. The latter has been shown to occur with metallic dopants like Fe and Ni in boron carbide.\textsuperscript{10} By network modification, metallic dopants simply fill the voids or interstitial positions in the B\textsubscript{12} icosahedral network, and contribute their valence electrons to B\textsubscript{12} icosahedra through charge transfer. The Al and Mg probably follow a similar mechanism in AlMgB\textsubscript{14} films as well. Fe impurities may also act as donors in these films, just as they do in boron carbide and $\beta$-rhombohedral boron.

Figure 1 shows $\ln I$ versus $1/T$ for the AlMgB\textsubscript{14} films. A well-defined linear behavior is evident, which is somewhat unusual given an amorphous semiconductor with complex composition, as such a “clean” doping behavior suggests that a single donor level is providing the conduction electrons. The activation energies are 0.13 eV for the room-temperature-deposited AlMgB\textsubscript{14} film and 0.17 eV for the 573 K-deposited AlMgB\textsubscript{14} film, indicating that the Al, Mg, and/or Fe introduce a donor level below the conduction-band edge. Due to the presence of minor amounts of Si (<1 at. %) in these films, the likelihood that Si is also a donor must be considered. Figure 2 shows $\ln I$ versus $1/T$ for baseline AlMgB\textsubscript{14} films, i.e., without Si. The activation energies are 0.11 eV for the room-temperature-deposited film.

![Graph 1](image1.png)

**FIG. 1.** $\ln I$ versus $1/T$ for the room-temperature- and 573 K-deposited Si-doped AlMgB\textsubscript{14} films.

![Graph 2](image2.png)

**FIG. 2.** $\ln I$ versus $1/T$ for the room-temperature- and 573 K-deposited baseline Si-free AlMgB\textsubscript{14} films.
and 0.19 eV for the 573 K-deposited film, suggesting that Si, however, does not have any impact on the transport properties of AlMgB14 films, at least not to the extent of metallic atoms.

Transformation of intrinsically $p$-type boron-rich boride materials to $n$-type by doping is not a trivial task because of the difficulty in overcompensating for the high-density trap states in the band gap; an extremely high donor concentration, on the order of $10^{20}$ cm$^{-3}$, is generally required to enable this transformation. In this study, however, $n$-type carriers were obtained in AlMgB14 films at much lower donor concentrations. This is probably because the six intrinsic trap states, which basically depend on the vibrational modes of B$_{12}$ icosahedra, were not fully developed at the low deposition temperatures. Figure 3 shows the Tauc plots of AlMgB14 films, from which the optical band gaps are determined to be $\sim$0.5 eV, and it appears that the deposition temperature does not have a strong effect on the optical gaps. Therefore, the different carrier concentrations in AlMgB14 films can only be attributed to the trap states of different characters, i.e., an increase in deposition temperature leads to a higher density of well-formed B$_{12}$ icosahedra, which, in turn, gives rise to more electron trap states in the gap. As the density of these trap states increases, a decrease in carrier concentration is expected, which is indeed observed in this study.

In summary, amorphous AlMgB14 films produced by PLD show an unusually low resistivity. The high $n$-type carrier mobility demonstrates that the electrical transport is due mainly to band conduction by electrons, which are contributed by Al, Mg, and/or Fe donor states. The electrical properties of AlMgB14 films are affected by the deposition temperature in such a manner that higher deposition temperatures tend to favor development of trap states in the band gap, hence resulting in a lower carrier concentration.

The work at Ames Laboratory was supported by the Director for Energy Research, Office of Basic Energy Science. Ames Laboratory is operated by Iowa State University for the U.S. Department of Energy under Contract No. W-7405-ENG-82.