Electrical Properties of Amorphous Si$_{0.60}$Ge$_{0.40}$:H$_x$ Films

B. A. Najafov* and G. I. Isakov**

* Institute of Radiation Research, Academy of Sciences of Azerbaijan, pr. Javida 31a, Baku, AZ1143 Azerbaijan
** Institute of Physics, Academy of Sciences of Azerbaijan, pr. Javida 33, Baku, AZ1143 Azerbaijan

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Abstract—Amorphous Si$_{0.60}$Ge$_{0.40}$:H$_x$ films containing 1.7, 3.9, 7.1, 12.1, and 17.3 at % H are prepared by magnetron sputtering at different hydrogen partial pressures, and their electrical conductivity is measured from 80 to 350 K. The conductivity data are used to evaluate the electron localization radius, hop distance, and activation energy of hopping conduction at 80 K; the electron mobility at the Fermi level and in the conduction band; and the 300-K activation energy of conduction.

INTRODUCTION

There is currently intense research interest in hydrogenated amorphous films of Si and Si–N, Si–C, Si–Ge, Si–O, and Si–Ge–C solid solutions.

In semiconductor electronics, particular attention has focused on a-Si$_{0.60}$Ge$_{0.40}$:H$_x$ solid solutions [1]. Hydrogenated amorphous films of Si–Ge solid solutions have a narrower band gap in comparison with a-Si:H, and hence, better optoelectronic properties in the long-wavelength portion of the visible range. In addition, they are thermodynamically more stable and offer higher radiation hardness [2, 3], which makes them attractive materials for solar cells [4–6].

The electrical properties of hydrogenated amorphous Si–Ge films have been studied extensively [6–12]. Compositions containing less than 40 at % Ge are believed to be the best suited for the fabrication of solar cells. a-Si$_{0.60}$Ge$_{0.40}$:H$_x$ is of interest as a material for photovoltaic applications.

The density of states in the band gap of amorphous Si–Ge films containing no hydrogen is known to be rather high [13]. To reduce it, such films are produced in hydrogen atmosphere or hydrogenated after growth. In addition, the introduction of hydrogen during film growth makes it possible to control the band gap of the material.

Electron paramagnetic resonance (EPR) [1, 14] and IR absorption data [15] indicate that the passivating properties of hydrogen in a-Si are better than those of hydrogen in a-Ge. For this reason, the photoresponse of hydrogenated Si–Ge films is somewhat weaker than that of a-Si:H films. H–Si bonds play a key role in passivating dangling bonds of germanium atoms, as evidenced by the weakening of the Staebler–Wronski effect with increasing Ge concentration (up to 40 at % Ge) [1].

The objective of this work was to study the effect of hydrogen concentration on the electrical properties of a-Si$_{0.60}$Ge$_{0.40}$:H$_x$ films and to determine the electron localization radius $\alpha$ near the conduction band edge $E_c$, Fermi-level density of states $N(E_F)$, hop distance $R$, activation energy $E_a$ of hopping transport, electron mobility $\mu_c$ (near the conduction-band edge $E_c$), and activation energy of electrons $\Delta E_a$ in the films.

EXPERIMENTAL

a-Si$_{0.60}$Ge$_{0.40}$:H$_x$ films 1 μm in thickness were grown by magnetron sputtering (Institute of Radiation Research, Academy of Sciences of Azerbaijan) at a substrate temperature of 180°C, deposition rate of ~3 Å/s, and target–substrate distance of ~25 cm. The process was run for ~1 h. In electrical measurements, the electric field was no greater than 10 kV/cm. The substrate temperature was monitored with a Chromel–Alumel thermocouple. The absorption coefficient in the spectral range studied attained 7 × 10$^4$ cm$^{-1}$ [16]. The band gap $E_g$ varied in the range 1.32–1.52 eV, which was due to the reduction in the density of localized states in the band gap.

The thickness of the a-Si$_{0.60}$Ge$_{0.40}$:H$_x$ films was determined optically, from the spacing between interference fringes [5, 14]. The hydrogen content of the films, evaluated from effusion and absorption data [5, 14, 15], was 1.7 to 17.3 at %. The films were deposited at different hydrogen pressures.

Our experimental results were used to optimize the deposition and hydrogenation conditions. The hydrogen plasma was generated using a magnetron and rf field.

The target used was a crystalline Si$_{0.60}$Ge$_{0.40}$ plate 60–63 mm in diameter. The amorphous state of the
RESULTS AND DISCUSSION

In the range 80–350 K, the Arrhenius plots of conductivity show two distinct portions (Fig. 1). Above 250 K, the conductivity exhibits Arrhenius behavior, 

\[
\sigma_T = \sigma_0 \exp\left(-\frac{\Delta E_a}{kT}\right),
\]

with the preexponential factor \(\sigma_0\) varying from \(8.91 \times 10^2\) to \(5.62 \times 10^1\) S/cm (Table 1).

Increasing the hydrogen content reduces the slope of the Arrhenius plot (Fig. 1), which points to electronic conduction since \(\Delta E_a = E_c - E_F\) for electrons. Below 250 K, charge transport is dominated by hopping conduction between localized states in the band gap, as evidenced by the linear variation of \(\log(\sigma T^{1/2})\) with \(T^{-1/4}\) (Fig. 2). Similar results were reported by Bahl and Bhagat [16]. Knotek et al. [17] measured the conductivity of silicon films in the hopping regime directly during deposition in ultrahigh vacuum and obtained \(\sigma \sim T^{-1/3}\). The conductivity of our films decreases with increasing hydrogen content over the entire temperature range studied. At high temperatures, the effect of hydrogen content on the conductivity of the films is

**Table 1. Parameters of \(a\)-Si\(_{0.60}\)Ge\(_{0.40}\):H\(_x\) films at 300 K**

<table>
<thead>
<tr>
<th>Film no.</th>
<th>at % H</th>
<th>(\sigma_0), S/cm</th>
<th>(\sigma_1), S/cm</th>
<th>(\Delta E_a), eV</th>
<th>(E_g^{\text{opt}}), eV</th>
<th>(\mu_F), cm(^2)/(V s)</th>
<th>(\mu_c), cm(^2)/(V s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7</td>
<td>(8.91 \times 10^2)</td>
<td>(1.78 \times 10^{-3})</td>
<td>0.62</td>
<td>1.52</td>
<td>(9 \times 10^{-1})</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>(6.31 \times 10^2)</td>
<td>(5.62 \times 10^{-4})</td>
<td>0.66</td>
<td>1.56</td>
<td>(5.114 \times 10^{-3})</td>
<td>(6 \times 10^{-1})</td>
</tr>
<tr>
<td>3</td>
<td>7.1</td>
<td>(2.82 \times 10^2)</td>
<td>(4.47 \times 10^{-5})</td>
<td>0.74</td>
<td>1.60</td>
<td>(5.704 \times 10^{-3})</td>
<td>(3 \times 10^{-2})</td>
</tr>
<tr>
<td>4</td>
<td>12.1</td>
<td>(1.26 \times 10^2)</td>
<td>(3.98 \times 10^{-6})</td>
<td>0.82</td>
<td>1.65</td>
<td>(9 \times 10^{-3})</td>
<td>(9.1 \times 10^{-2})</td>
</tr>
<tr>
<td>5</td>
<td>17.3</td>
<td>(5.62 \times 10^1)</td>
<td>(5.62 \times 10^{-7})</td>
<td>0.87</td>
<td>1.72</td>
<td>(2.5 \times 10^{-4})</td>
<td>(2 \times 10^{-3})</td>
</tr>
</tbody>
</table>

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\(\Delta E_a\) = Excitation energy from valence band to conduction band.

\(E_g^{\text{opt}}\) = Optimum band gap energy.

\(\mu_F\), \(\mu_c\) = Field and carrier mobilities, respectively.