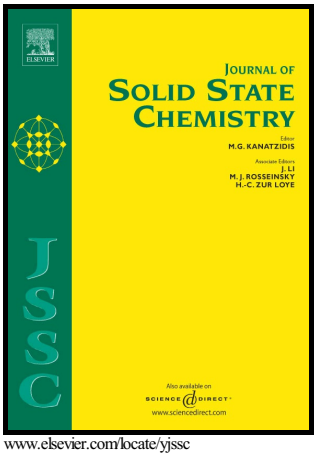

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Solid State Synthesis of Mn_5Ge_3 in Ge/Ag/Mn trilayers: Structural and magnetic studies

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ABSTRACT
The thin-film solid-state reaction between elemental Ge and Mn across chemically inert Ag layers with thicknesses of (0, 0.3, 1 and 2.2 μm) in Ge/Ag/Mn trilayers was studied for the first time. The initial samples were annealed at temperatures between 50-500 °C at 50 °C intervals for 1 hour. The initiation temperature of the reaction for Ge/Mn (without a Ag barrier layer) was ~ 120 ºC and increased slightly up to ~ 250 ºC when the Ag barrier layer thickness increased up to 2.2 μm. In spite of the Ag layer, only the ferromagnetic Mn_5Ge_3 compound and the Nowotny phase were observed in the initial stage of the reaction after annealing at 500 °C. The cross-sectional studies show that during Mn_5Ge_3 formation the Ge is the sole diffusing species. The magnetic and cross-sectional transmission electron microscopy (TEM) studies show an almost complete transfer of Ge atoms from the Ge film, via a 2.2 μm Ag barrier layer, into the Mn layer. We attribute the driving force of the long-range transfer to the long-range chemical interactions between reacting Mn and Ge atoms.

Graphical Abstract
The direct visualization of the solid state reaction between Mn and Ge across a Ag buffer layer at 500 °C

Keywords: Long-range atomic transfer; Mn-Ge system; Thin-film solid-state reaction; Diffusion barrier; Dominant diffusing species; First phase ; Mn_5Ge_3 alloy

1. Introduction

Although thin films have been widely used in advanced electronic devices, the atomic migration during thin-film solid state reactions continues to be the subject of many investigations [1-5]. Numerous studies of solid-state reactions in nanofilms showed that there are three fundamental features that strongly distinguish them from bulk samples:
(i) Formation of only the **first phase** at the film interface at a certain temperature T_{in} called the **initiation (formation) temperature** T_{in}. As the annealing temperature increases, other phases can occur and form the phase sequence [3-8].
(ii) The threshold of the reaction, characterized by intense intermixing at the interface and the formation of compounds, arises at temperatures above the initiation temperature T_{in} [3-5].
(iii) Migration of the dominant diffusing species through the interface during the first phase formation [5, 9, 10].

The formation of only the first phase among the equilibrium phases, the low initiation temperatures that can be below room temperature [11, 12] or even below 90 K [13-16] and the migration of the dominant diffusing species are unique, unexplained features of solid-state reactions in nanofilms. As discussed above, the initiation temperature T_{in} is the threshold temperature. This means that there is no reaction below T_{in} and the reaction initiates just as the