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Null-ellipsometry investigations of the optical properties and diffusion processes in spin-valve structures based on Co and Cu

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ABSTRACT

The influence of annealing temperature ($T_a = 300–900$ K) on optical properties of the Au (4 nm)/Co (3 nm)/Cu (6–12 nm)/Co (20 nm)/SiO_2/Si spin-valve structures was studied. The model of Co, Au, and Cu atom interdiffusion was proposed based on the experimental data analysis. The formation of solid solutions at the thin layer interfaces Au/Co and Cu/Co was studied, and as a result the most intensive formation of solid solutions was identified at annealing temperature of $T_a = 750$ K. The optical parameters of the samples were calculated using the genetic algorithm. The spin-valve systems remain relatively unperturbed until 750 K, but the optical properties change significantly from 750 to 900 K. It can be explained by the formation of the interphase in multilayer thin film systems.

1. Introduction

Null-ellipsometry method is used to study the optical properties of multilayer metal film systems [1,2]. On the basis of this method, the principal azimuth angle Ψ and the phase difference Δ are calculated at the given angle of incidence θ. The number of parameters, which characterize multilayer film structure, such as the thickness d and the indexes of film refraction $n + ik$, can be found by solving the inverse problem of ellipsometry. But in the case of the multilayer structure this method can generate many possible solutions. Therefore, in order to get the most reliable results, the genetic algorithm (GA) is more preferable for ellipsometric data analysis. The combined GA, as well as the Levenberg–Marquardt gradient method was used in Ref. [3], also this algorithm is widely used for optimization problems [4]. Nowadays GA is implemented with the help of C, C++, LabVIEW, Java, MatLab and other software. We have used the modified program libraries of GA developed at the International Institute of Computer Sciences in Berkley (California) [5]. The main rules and recommendations for the usage and program implementation of GA can be found in Refs. [5–7]. Ellipsometry method is used not only for the determination of the properties of each film layer in the multilayer structure, but also for the study of the formation process of the grained solid solution intermediate layers [8] and high accuracy estimation of their properties such as the thickness and optical parameters [3].

Multilayered structures, film grained alloys and spin-valve structures with spin-dependent electron scattering based on Co and Cu or Au are widely used in up-to-date micro-instrument engineering and sensor techniques as sensing elements for high density recording systems [9]. Magnetic properties of spin-valve structures attract great interest due to the giant magnetoresistance effect [10,11] and mechanical strain effect [12,13]. But besides that, the structural properties of multilayer film systems with spin-dependent electron scattering as well as interdiffusion and formation of intermediate layers of grained solid solutions are also important scientific problems. The volume concentrations of Co and Cu in two-layer system have a strong effect on lattice constant due to the formation of a solid solution in the samples [14]. Transmission electron microscopy is a widespread method for solid solutions' investigation. But at the same time this method has some disadvantages, because it does not allow one to analyze the formation of intermediate layers during annealing and to identify the interface boundary between layers.

The main aim of the present work is to study interdiffusion in multilayer structure and intermediate layer formation, as well as to develop the software which enables one to find the refractive indexes and the layer thicknesses of Au/Co/Cu/Co/SiO_2/Si multilayer spin-valve film structures using GA.

As a rule, the X-ray diffraction and reflectometry methods are used for the precise measurement of the thicknesses of separate layers in the multilayer structure [15–17], and therefore the GA is very suitable for the analysis of the experimental results. But in the case of the spin-valve structures based on Co/Cu, the X-ray reflectometry method gives an inaccurate measurement of the base and intermediate layer thickness and roughness of the interface because densities of Co and Cu are almost similar. We used null-ellipsometry

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as an additional experimental method to study Co and Cu layers, since their optical indexes are different in visible light range.

2. Experimental details

The present work is devoted to the investigation of the spin-valve structures deposited by electron-beam evaporation in ultra-high vacuum of 10^{-7} Pa onto Si(100) wafers with natural SiO_2 oxide. The layer thickness during the deposition process was controlled by the quartz resonator method, and Cu layer thickness in spin-valve structures is varied within the range from 6 to 12 nm.

We have carried out a series of ellipsometric measurements of spin-valve structures depending on the treatment temperature using Pfeiffer Vacuum plant under the residual gas pressure of 10^{-7} Pa. The annealing was performed using Tectra HTR1001 heating element and Tectra HC3500 controller with proportional-integral-derivative regulator. The annealing temperature varied from 450 to 900 K with a ramp of 0.05 K/s. Null-ellipsometer with THORLABS optical elements was used for our experimental study. All of the measurements were carried out at the angle of incidence of 70° and the wavelength $\lambda = 632.8$ nm. Developed null-ellipsometer provides accuracy of Δ and Ψ measurements not worse than 0.01°, and this corresponds to the calculation error of multilayer structure effective thickness of the order of 0.01 nm.

3. Calculation

The proposed software has been developed in LabVIEW 2009 programming environment by National Instruments.

Fig. 1 shows the block diagram of the solution of the inverse ellipsometric problem using GA. For the solution of the inverse ellipsometric problem the Parratt model [18] was used as well.

The main task of the algorithm is to find the parameters of the model at which the *cost function* will be the minimum one. On the first stage the sets of initial random population are generated in a quantity specified by the user only for those parameters where it is required. As a result, the two-dimensional array of initial randomly generated populations is obtained.

The feature of this stage is that the initial random population parameters, if they are necessary, can be generated in a narrow min–max range specified for each parameter separately. In this case the values of generated parameters are close to the possible solutions that lessen the time required to find the final solution. Then, the generated two-dimensional array is sent to the *cost function* calculation subprogram, which enables one to find the maximum error and deviation from the model for each individual generated population. The general relationship for the *cost function* calculation can be represented as follows:

$$cost\ function = A\left(\left|\Delta - \Delta_{exp}\right|\right)^{n_1} + B\left(\left|\Psi - \Psi_{exp}\right|\right)^{n_2} + C(|\Delta n|)^{n_3} + D(|\Delta k|)^{n_4} + E(|\Delta d|)^{n_5}, \quad (1)$$

where *cost function* is the total error and deviation of the generated population with respect to the preset model and specified experimental values of Ψ_{exp} and Δ_{exp}; calculation parameters Ψ, Δ, n, k and d are the main azimuth, phase difference, $n + ik$ refraction index and layer thickness, respectively; A, B, C, D, E and indexes of power n_1–n_5 are the weight parameters, which contribute to the total *cost function*; deviation of Ψ and Δ parameters from experimental values Ψ_{exp} and Δ_{exp} and deviation of calculated parameters from n_{min}–n_{max}, k_{min}–k_{max} and d_{min}–d_{max} intervals.

On the next stage, among all generated populations the best one (that has the minimum value of the *cost function*) is chosen. Based on this GA, a new array of population parameters is formed by means of mutation, substitution and recombination. New populations are sent to the *cost function* calculation subprogram, and then the loop

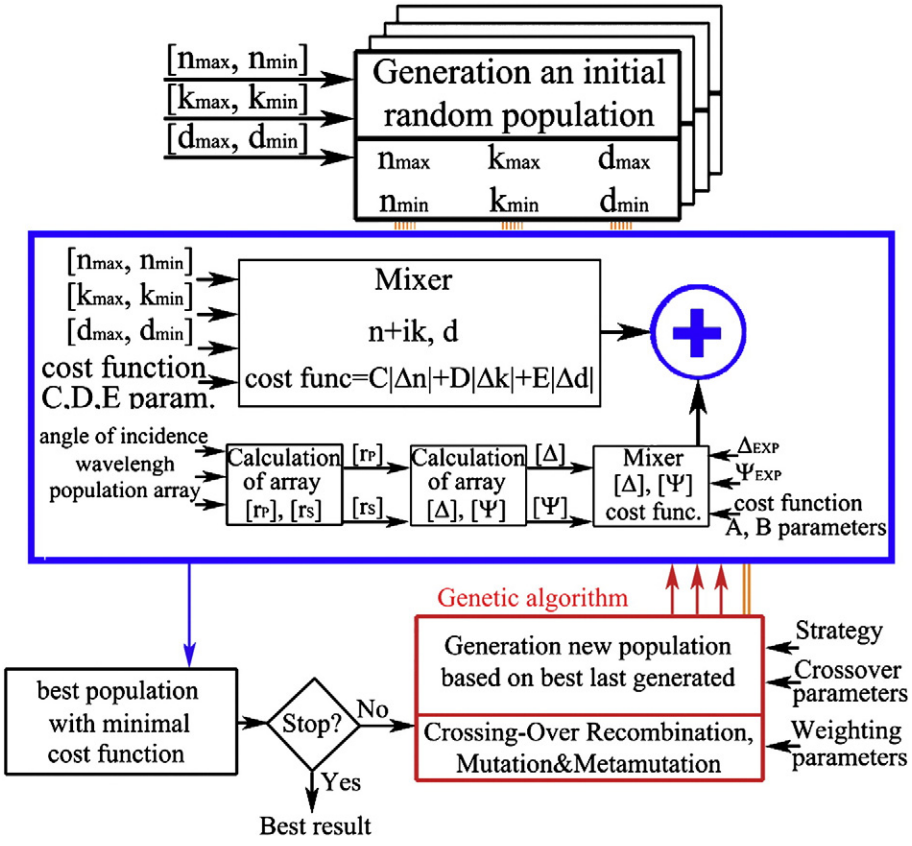

Fig. 1. The block diagram of the inverse ellipsometric problem solution using GA.