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Morphology changes due to AC induced electromigration in Gd islands on W(1 1 0)

H. Realpe [a,c], N. Shamir [b,*], M.H. Mintz [b,c], Y. Manassen [a]

[a] *Department of Physics and the Ilse Katz Center of Science and Technology in the nm Scale, Ben Gurion University of the Negev, P.O. Box 653, Beer Sheva 84104, Israel*

[b] *Nuclear Research Center – Negev, P.O. Box 9001, Beer Sheva 84190, Israel*

[c] *Department of Nuclear Engineering, Ben Gurion University of the Negev, P.O. Box 653, Beer Sheva 84104, Israel*

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Abstract

Gd islands were grown on W(1 1 0) surface by evaporating Gd on the substrate at room temperature and subsequent annealing. STM images reveal in many cases islands which have a deep hole inside them. The appearance of the hole is associated with the application of an AC field. No such holes appear when the sample is heated by a DC current. We show that this can be explained by the combined affect of the AC field and the barrier to diffusion introduced by steps that can create a nucleus for further growth of an island which includes a hole in the middle. This may be generalized to a technique of tailoring the size, shape and distances of islands by, for example, two orthogonal AC fields with a phase delay of 90° between them.

Keywords: Gadolinium; Scanning tunneling microscopy; Surface thermodynamics; Surface morphology

The transport of matter in metals (mainly) and semiconductors under the influence of a DC current, known as electromigration has a significant (negative) technological importance due to its contribution to failure of electronic circuits. This is becoming even a more important problem due to device miniaturization and increasing current densities. This effect manifests itself as a bias of diffusion of atoms and defects induced by an external electric field [1]. This effect was detected in hydrogen in palladium [2] many years ago. It is understood now, that the electromigration occurs due to the momentum exchange between the conduction electrons and the atoms. This electromigration process, that can be quite significant, can occur both in the bulk (where most studies were performed) and the surface. This process was described as a result of drag forces that were applied by the moving medium of the conduction electrons on the static atoms. Therefore these forces are called wind forces. As one may expect, these forces have a significant influence on the mobility of the electrons too and consequently also on the resistivity of metallic surfaces [3]. Since these two phenomena originate from the momentum exchange between the drifting electrons and the adatoms, it is possible to calculate them simultaneously [13].

The exact estimation of the magnitude of these forces is a very complicated problem and it was discussed by many theoretical works [4–13]. The magnitude of the wind force was estimated by a broad variety of computational techniques. Electromigration is described, using the empirical law $F = eE(Z_d + Z_w)$: In this formula, the force (F) applied on the migrating ion is proportional to the external applied electric field (E). The first contribution to the driving force of the field is related to the valence of the ion (Z_d) and can be considered as the direct interaction of a charged ion with an external applied field. The second, more subtle, force is due to momentum exchange between the electrons and the ion, and it is expressed in terms of the wind valence Z_w.

* Corresponding author. Tel.: +972 8 6568785; fax: +972 8 6568751.
E-mail address: noah.shamir@gmail.com (N. Shamir).

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The wind force is usually much larger, and is dominant in most electromigration cases.

A straightforward solution to bulk electromigration in a free electron picture is given by the ballistic model [4]. The magnitude of the wind valence can be estimated as $Z_w = -n_0 l\sigma_{tr}$ where n_0 is the electron concentration, l is the electronic mean free path and σ_{tr} is the transport cross section of the adatom at the Fermi energy. Using typical values for light metals we get $Z_w = -10$. These wind forces have many peculiar properties. As an example, when diffusion on Na(100) was considered, heavier metals such as W have a wind valence which is larger by more than one order of magnitude than light metals. A dependence of the wind valence on the diffusion path was found [10]. Another paper [11] predicts a twofold increase in the wind valence parameter when aluminum atoms are near a single step of aluminum (aluminum is commonly used as an electrical interconnect) – compared to an isolated atom on a terrace. This is a general phenomenon: The shadowing of atom, island, step etc, on a neighboring adatom is expected to modify significantly the wind force valence term Z_w, which can be written in these cases, as a tensor, namely drag forces in other directions than the direction of external electric field may appear [12]. In addition to inducing electromigration of adatoms, similar wind forces can induce motion of vacancies as well as other defects or impurities, both in the bulk and on the surface.

In all these cases, only DC voltage was discussed to create diffusion bias in the direction of the field. However, since wind forces can create a relatively significant biased diffusion, we discuss in this paper the induction of electromigration in quasi circular paths as a result of an AC current. This may lead to a possibility to shape the size, the shape and the inter-island spacing with AC current. It should be possible, for example, to connect a (rectangular) crystal with four orthogonal electric contacts and to apply time dependent voltages and currents in such a way that the diffusion is biased each time in a different direction. If we increase the frequency of the AC fields, for example smaller islands might be formed on the surface. In all these cases, the (closed-quasi circular) biased diffusion competes with the random component of the diffusing atom (or vacancy), however, since the applied fields can be large, and there are significant (for example elastic) interactions between the islands, this together with the bias diffusion can provide quite a strong tool for modifying the island's shape, size and inter-island distribution.

The affect of AC current on the morphology of islands is demonstrated in following experiment: We deposited several monolayers of a rare earth material (gadolinium) on top of a metallic crystal (W(110)). After deposition, we applied a strong AC field along the sample. In addition to this the crystal has steps that has a certain angle (namely they are not parallel, nor perpendicular) with the direction of the field. These steps are expected to create a significant barrier to diffusion also, in particular in the downhill directions (the Schwoeble barrier). Thus the combination of the biased diffusion of the field, together with the biased diffusion along the step, can drive the atoms into closed-quasi circular paths, which will alter its final shape. The evidence that this process did indeed occur, is a deep hole, created in the center of the island, which has a very peculiar shape, and appears only when the crystal is heated with a strong AC field. Some of these islands are shown in Fig. 1. We have also done DC heating and did not observe such shapes. A typical image with DC heating is shown in Fig. 2.

The experiment was performed in a UHV system (base pressure: 5×10^{-10} mbar). Gadolinium was epitaxialy grown on a clean W(110) substrate: 2–5 monolayers of Gd were deposited on the substrate at room temperature using an electron gun.

In order to clean the tungsten crystal and to anneal it after Gd was deposited a special heating system was constructed. The heating was made though resistive heating by passing currents close to 100 A through the sample supporting currents for annealing and flashing. The heating stage shown in Fig. 3, is specially designed in order to reach temperatures of several thousands degrees.

Afterwards, the sample was annealed by either an AC current (40 A and a bias voltage of 60 V – at 50 Hz) or similar DC currents to a temperature of 650 °C. In all the steps of this process the sample was characterized by AES to verify that the sample was clean before the deposition and to characterize quantitatively the deposition process, indicating that the islands grow as three-dimensional isolated Gd islands on the tungsten surface. Finally, using an STM [14], the surface of the sample was imaged in constant current mode. It was observed that after annealing by AC, Gd islands were formed with heights 2–14 ML. Fig. 1 shows several STM images in which a bi-modal size distribution of islands is observed (Fig. 1c–e) – small and thin islands and bigger and thicker ones, in which it is possible to identify a peculiar morphology: they appear to contain a relatively deep hole, and a kind of an adjacent balcony, lower than the main island.

The size of the hole is, on the average, 5 nm in diameter and several nm deep. Thus the hole cannot be explained in terms of a difference in the local density of states (as opposite to topography). If one compares the positions of the holes with the positions of the center of mass of the islands (Fig. 4), we see two asymmetric features in the position of the holes. The first is that the holes are distributed to a larger extent along the terraces of the W(110). This can be explained by the fact that the islands themselves are also asymmetric and are longer along the direction of the terraces. Additionally, there is an asymmetry in the positions of the holes in the lateral direction. We recall that in all of our images, the higher terraces are located on the right-hand side of the lower ones. Most of the holes are located closer to the right-hand edge of the island (compared to the center of mass). This asymmetry can be easily understood if one considers the asymmetry of the Schwoeble barrier, which forms a smaller barrier to diffusion in the uphill direction (as compared to downhill direction). This means