Application of High Power Ion Beam for Formation Conductivity Nanoparticles on Surface of Dielectric

V.S. Kovivchak***, R.B. Burlakov**, and T.V. Panova**

*Omsk Branch of the Institute of Semiconductor Physics SB RAS, Omsk, 644018, Russia
**Omsk State University, 55a, Mira ave., Omsk, 644077, Russia

Abstract – The formation of nanoparticles in a thin metal film-dielectric substrate system under the action of a high-power ion beam of nanosecond duration was studied. Data on the particles formed from 5- to 300-nm-thick aluminum and nickel films on ST-50 Sitall (glass-ceramic composite) and soda-lime glass substrates are presented. Possible mechanisms of nanoparticle formation in ion-irradiated metal films on dielectric substrates are considered.

1. Introduction
At present, the study of nanoparticle systems is very important from the point of view of fundamental and applied sciences, because these systems have unique properties differing from those of bulk material. Ni and Fe metal nanoparticles are used in catalytic growth of carbon nanotubes, and Ag, Au, and Cu nanoparticles can be used in devices based on surface plasmon resonance. There exist many methods for producing nanoparticles, namely, chemical reduction, laser ablation, thermal deposition, ion implantation, and thermal annealing. Each of these methods has its own benefits and limitations. In our opinion, methods using various short-pulse thermal actions on a system containing a thin metal film on a dielectric substrate are most promising. Laser or ion beam induced melting of thin film can lead to the development of instability, resulting in the breakage of a film and the formation of drops in cases where the melt poorly wets the substrate. Using chemically inert material as substrate, it is possible to obtain drops of various metals on the substrate surface.

In this work, we study the possibility of producing metal nanoparticles and their conglomerates by irradiating a system consisting of a thin metal film on a dielectric substrate with a high-power ion beam of nanosecond duration.

2. Technique of experiment
Al and Ni thin films deposited on substrates made of ST-50 glassceramic and soda-lime glass were used as objects in our study. The metals used in our study have very different thermodynamic characteristics and chemical properties (melting temperature, capability of forming an oxide, and adhesion to a substrate). The thickness of films obtained by thermal evaporation in a vacuum was varied from 5 to 300 nm. The substrates were cleaned chemically in a standard way before deposition of coatings performed at substrate temperatures not above 150 °C. A Temp accelerator was used for irradiating the samples with a 300-keV proton–carbon beam (30% H+ and 70% C+) at an average current density of up to 150 A/cm² and an irradiation duration of 60 ns. The film thickness and the irradiation regime (the average current density and the number of irradiation pulses) were varied in our experiments. The coating thicknesses were much less than the carbon and proton ion path in the film material, while the substrate thicknesses were much greater than the beam ion path. The surface morphology of irradiated materials was studied by the optical microscopy method using Neophot-2 and Biomicroscopes as well as a Solver Pro atomic-force microscope (AFM).

3. Results and their discussion
The character of the interphase interaction in the metal–substrate system, the heat conductivity of the substrate, the initial metal film thickness, the surface tension, and the viscosity of the melt are the parameters that determine to a significant extent the formation of an array of metal drops (islands) on the nanoscale [1, 2].

However, the relatively small depth of the penetration of laser radiation into a metal film, a change in the coefficient of laser radiation reflection during melting of the film, small beam cross-section area, and some other factors restrict the range of metal film thicknesses that can be used for the laser-induced formation of metal particles of controlled size on a substrate. Therefore, it is important to study processes in thin metal films on dielectric substrates under the action of high power ion beams. Such beams possess a number of advantages in comparison to laser radiation, including higher penetration ability (which ensures the heating of both the film and a surface layer of the substrate), independence of the ion range of the state of the target surface, a high degree of absorption in all metals, and the possibility of processing large-area targets.

During the action of a high power ion beam on a metal film, the thickness of which is comparable with the projected ion range, a significant fraction of the beam energy is absorbed in the film that can lead to its melting. Previously, we have demonstrated [3] that metal films with mirror finishes on a dielectric substrate under the single high power ion beam irradiation...
with gradually increasing beam current density exhibit a sequence of substantial morphological changes, which include cracking of the film, the appearance of bare substrate areas upon melting of the film (Fig. 1, a), and the formation of a cellular structure (Fig. 1, b) and eventually of a pattern of metal drops of various shapes and dimensions (Fig. 1, c). Recently, we have established that, when the beam current density exceeds \(30 \text{ A/cm}^2\), a wavy structure may be formed on the substrate surface (for example, SiO\(_2\)/Si) in addition to various metal particles [4].

Figure 2 shows the typical AFM image of the surface of a 60-nm-thick Al film on sitall substrate after irradiation to a single pulse of a high power ion beam with a current density of \(20 \text{ A/cm}^2\). The action of the pulsed ion beam leads to the formation of disk-like Al particles on sample surface. Data on the characteristic dimensions of particles (including the most probable diameter \(d\) and height \(h\) and the average surface number density \(n\)) observed upon the action of beams with different current densities on various thicknesses metal films on sitall substrate are summarized in the Table I.

### Table I. Regimes of HPIB irradiation and parameters of nanoparticles

<table>
<thead>
<tr>
<th>Film material (thickness, nm)</th>
<th>Ion beam density, A/cm(^2)</th>
<th>(d), nm</th>
<th>(h), nm</th>
<th>(n), cm(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (300) 50</td>
<td>4850</td>
<td>410</td>
<td>7 \cdot 10^5</td>
<td></td>
</tr>
<tr>
<td>Al (60) 20</td>
<td>810</td>
<td>100</td>
<td>4.2 \cdot 10^7</td>
<td></td>
</tr>
<tr>
<td>Al (60) 10</td>
<td>250</td>
<td>52</td>
<td>8.5 \cdot 10^7</td>
<td></td>
</tr>
<tr>
<td>Al (20) 10</td>
<td>190</td>
<td>25</td>
<td>5 \cdot 10^8</td>
<td></td>
</tr>
<tr>
<td>Ni (15) 10</td>
<td>475</td>
<td>85</td>
<td>1.2 \cdot 10^8</td>
<td></td>
</tr>
<tr>
<td>Ni (5) 10</td>
<td>84</td>
<td>48</td>
<td>3.5 \cdot 10^8</td>
<td></td>
</tr>
</tbody>
</table>

The particles are formed due to the collection of a melted metal from the adjacent regions of the substrate surface.

The parameters of Al particles determined in experiments are in good agreement with estimates calculated using the given Al film thickness and the surface density of particles. Upon the exposure of a 60-nm-thick Al film to an ion beam with a lower current density (10 A/cm\(^2\)), regions of continuous film with a strongly deformed surface were observed on the sample in addition to the separate particles. The diameters of such regions were about 1.0–1.5 \(\mu\)m. Their appearance is probably explained by insufficient heating of the film of indicated thickness by the ion beam of reduced current density and, hence, by a shorter period of time in which the heated metal occurred in the liquid state.

For the same beam current density of 10 A/cm\(^2\), a decrease in the film thickness leads to a significant decrease in the size of metal particles, but this is accompanied by the appearance of a large number of agglomerates consisting of several particles. This behavior is probably related to the fact that at smaller film thicknesses the mobility of a melted metal is
more significantly influenced by the natural oxide (Al₂O₃) formed on the melt.

An increase in the number of ion beam pulses leads to a decrease in the size of particles as a result of aluminum evaporation (provided that the temperature of intense evaporation is reached). However, the surface number density of Al particles also decreases, primarily because of a decrease in the fraction of particles with the minimum diameters.

By using nickel, which has a higher melting temperature (1726 K), as the film material, it is possible to realize conditions of the ion-beam-induced melting under which the melt exhibits a stronger interaction with the substrate surface.

Figure 3 shows the typical AFM images of the surface of Ni films of different initial thicknesses on siall substrates after exposure to a single pulse of a carbon–proton beam with a current density of 10 A/cm².

The characteristic parameters of particles formed in this system are also presented in the table. As can be seen from these data, the most probable height of particles in both cases exceeds the initial film thickness. The formation of such high (relative to the film thickness) metal islands is probably related to the interaction of melted nickel with the substrate surface softened under the action of the ion beam. Solidification of the metal is accompanied by the development of mechanical stresses, which lead to deformation of the softened substrate surface and the formation of protrusions covered by a layer of nickel.
The ion beam energy liberated immediately in Al and Ni films used in this study is very small (especially for Ni) and insufficient for their melting because of rather insignificant beam energy losses in the film. This is related to the fact that the film thickness is significantly smaller than the projected ranges of 300-keV carbon ions and protons, which amount to 573 and 2763 nm in aluminum and 270.6 and 1329.9 nm in nickel, respectively [5]. For this reason, the major fraction of the beam energy is deposited in the near-surface layer of the substrate. In the case of aluminum, which has a relatively low melting temperature (933 K) that is lower than that of the substrate material, it is possible that the metal is melted due to heat supply from the substrate.

However, this mechanism of the metal film melting without significant deformation of the substrate surface is less probable for Ni, which has a higher melting temperature than that of the substrate. The most probable mechanism of melting for ultrathin Ni films is that proposed by Hu et al. [6] for the melting and dewetting of 3- to 10-nm-thick films of platinum on SiO$_2$/Si substrates irradiated by a continuous beam of 800-keV Kr$^+$ ions. According to this mechanism, the energy losses of high-energy ions as a result of their interaction with electron and nuclear subsystems of the lattice lead to the local melting along the ion track. The local melting at the surface can significantly change the morphology of the metal film, since high temperature gradients lead to large gradients in the surface tension and local pressure, thus inducing intense mass transfer.

4. Conclusions

Thus, by selecting the appropriate thickness of a metal film on a dielectric substrate, the current density of a high-power nanosecond pulsed ion beam, and the number of pulses acting on the film, it is possible to obtain nanodimensional metal particles on the substrate surface. If the melting temperature of the metal is higher than that of the substrate, the ion irradiation leads to the formation of particles containing both the metal and the substrate material.

References