公開用要約

Laser nano ablation induced by the interaction of femtosecond laser with metal surfaces

Yasuhiro Miyasaka

Abstract

Femtosecond lasers are expected as equipment for high value added processing in the next generation because of discriminatory phenomena seen in ablation with them such as minimal thermal processes, extremely shallow ablation, and self-organized surface morphology. However, the mechanism of femtosecond laser ablation is not fully understood enough to control it actively. The ablation induced by a femtosecond laser is called “nano ablation”, because the depth of ablation induced by a single pulse (shot) are nanometer-scale. The femtosecond laser nano ablation process is so interesting that it deserves investigation from the viewpoints of laser-matter interaction physics and applications for highly sophisticated precision processing.

In the present work, we have studied the interaction of femtosecond pulse laser with metal surface. From the feature seen in the dependence of ablation rate on laser fluence, femtosecond laser ablation is discussed by classifying the fluence into three (low-, middle-, and high-) fluence ranges. Especially, all phenomena in the low-, and middle-fluence ranges are observed only for femtosecond laser ablation. To understand the mechanism of femtosecond laser ablation, (1) energy distribution of ions emitted from the metal under the laser irradiation in low-fluence range, (2) ablation rate dependence on laser incidence angle and polarization in the low-, middle-, and high-fluence ranges, and (3) the change of surface morphology in low-fluence range have been investigated experimentally.

(1) The ablation rate in low-fluence range is less than 0.1 nm/pulse. This denotes that the ablation in the low-fluence range is nonthermal process, which is different from evaporation observed in the middle- and high-fluence ranges. We have investigated the mechanism of ion emission from copper surface for the low-fluence range by measuring the energy distribution of ions by time-of-flight method since it is difficult to observe the transition of laser irradiated spot area directly. The copper ions emitted by the laser-copper metal interaction are nonthermally distributed in energy. The energy distribution is in

disagreement with thermal (Shifted Maxwell-Boltzmann) distribution, which is seen for nanosecond pulse laser ablation. By careful observation with FE-SEM, we have confirmed the existence of nanoparticles on target surface before laser irradiation. To interpret the nonthermal ion emission, we have proposed a mechanism of ion emission, that is, ions are emitted as a result of Coulomb explosion of nanoparticles on surface. The energy distribution of ions for this mechanism is well fit to the experimental results. We have known that the energy distribution of ions emitted from metal surface is controllable by optimizing the size distribution of nanoparticles on target surface.

(2) We have found that the quantity of emitted ions depends on laser polarization at oblique laser incidence. It is likely that the ablation rate depends on laser polarization and incidence angle as well as ion emission. However, the ablation rate has been reported only for normal incidence. The knowledge about the ablation rate is little. We have investigated the ablation rate dependences on laser incidence angle and polarizations for the low-, middle-, and high-fluence ranges. In high-fluence range, the ablation rate for *p*-polarized irradiation does not depend much on laser incidence angle, while that for *s*-polarized irradiation slightly decreases as incidence angle increase. In middle-fluence, the ablation rate increases a little for *p*-polarization and decreases much for *s*-polarization as the incidence angle is increased. Especially, the ablation rate for the *s*-polarized irradiation at an incidence angle of 70° is two orders of magnitude smaller than that at normal incidence. In the literature by today the ablation rate in middle-fluence range is conventionally interpreted by optical penetration depth, however, the optical penetration depth hardly depends on laser incidence angle. We have found that the ablation rate depends on laser incidence angle and polarization, and we have proposed new formulas to describe the ablation rate in middle-fluence range for irradiations at oblique incidence angles (including at normal incidence) for *p*- and *s*-polarizations. The simple formulas will be useful for future studies of laser processing, optics damage, and so on.

(3) The ions are emitted continuously with more additional pulse irradiations for higher fluence, which it comes to a stops for low fluence. From these results we have considered that nanostructures (nanoparticles) are generated by femtosecond laser irradiation to be the ion source. We have observed surfaces of tungsten, molybdenum, copper, and platinum by FE-SEM after laser irradiation at normal incidence in low-fluence range. Nanoparticles and nano-sized cracks are formed on the tungsten, molybdenum, and copper surfaces. As the number of pulses is increase, the density and the length of nanocracks increase. The directions of nanocracks are perpendicular to the laser

polarization. From the electromagnetic fields near the nanocracks, which is numerically calculated by the finite-difference time-domain method, it is proposed that laser electric field at the edge of nanoholes in direction perpendicular to the laser polarization is in fairly good agreement with the experimental results.

These research progress obtained in the present studies is of much significance and useful for future studies of laser-matter interaction physics and applications of laser processing.