Nuclear Instruments and Methods in Physics Research B 356–357 (2015) 75–80

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Aluminum multicharged ion generation from laser plasma

Md. Haider A. Shaim, Hani E. Elsayed-Ali *

Department of Electrical and Computer Engineering and the Applied Research Center, Old Dominion University, Norfolk, VA 23529, USA

ARTICLE INFO

Article history:
Received 24 November 2014
Received in revised form 24 April 2015
Accepted 25 April 2015
Available online 14 May 2015

Keywords:
Multicharged ion source
Laser ablation
Aluminum

ABSTRACT

Multicharged aluminum ions are generated by a ns Q-switched Nd:YAG laser pulse ablation of an aluminum target in an ultrahigh vacuum. Time-of-flight and electrostatic retarding field ion energy analyzers are used to detect the laser-generated multicharged ions. The experiments are conducted using laser pulse energies of 45–90 mJ focused on the Al target surface by a lens with an 80-cm focal length to 0.0024 cm^2 spot area and incident at 45° with the Al target surface. With the increase in the laser pulse energy, a slow increase in the number of ions generated is observed. The generation of ions with a higher charge state is also observed with the increase in the laser pulse energy. For 5 kV accelerating voltage applied to the Al target and using laser energy of 90 mJ, up to Al^{+4} with ~0.65 nC total ion charge is delivered to the detector which is located 140 cm away from the Al target. Raising accelerating voltage increases the charge extraction from the laser plasma and the energy of multicharged ions.

1. Introduction

Multicharged ion (MCI) sources are an emerging tool for nanoprocessing and nanofabrication [1]. MCI sources are being developed for various applications that include ion implantation, ion deposition, and cancer therapy [2]. Multicharged ions can be used to modify the surface properties, such as roughness, hardness, electrical conduction, and chemical reactivity [3]. For singly-charged ions at kinetic energies lower than ~5 keV, the interaction is dominated by ion projectile–target nuclei interactions, resulting in surface sputtering, intermixing, and defect generating [4]. The higher charge state MCI has significant potential energy that is equal to the sum of ionization energies of stripped electrons. When interacting with a solid, MCI can release its potential energy along with the kinetic energy. For ultraslow highly charged ions, this potential energy could be considerably higher than the kinetic energy. During ion interaction with the surface, the MCI potential energy causes electronic exchange interaction along with the electronic excitation [5]. The release of this potential energy can be localized to a depth of a few nm from the surface for sufficiently slow MCI and, therefore, can be channeled into the generation of surface nanofeatures. With MCIs, it is possible to independently control the kinetic and potential energy of the ions. This property makes the MCI sources an important tool in the areas of nanotechnology, microelectronics, and semiconductor processing.

High current MCIs are produced in electron cyclotron resonance ion sources (ECRIS) [6], electron beam ion sources (EBIS) [7], and laser multicharged ion sources (LMCI) [8,9]. While both ECRIS and EBIS generate MCIs from gases or external ion or laser ablation sources; therefore, they cannot be directly used for ion production from solids, which adds an extra step for MCI generation from solid targets. The laser MCI sources produce plasma plume by laser ablation and ionization of a solid target. The laser MCI system and its transport line can be operated in ultrahigh vacuum (UHV) with a relatively small pumping capacity since no gas load is handled and no differential pumping is needed. The availability of many pulsed laser deposition systems makes it possible to reconfigure these systems into laser MCI sources.

Several groups have developed laser MCI sources. For ablation of an aluminum target with 7 ns Nd:YAG laser pulse, 1064 nm wavelength with laser intensity of 8.7×10^{10} W/cm^2, Abdellatif et al. reported that the plasma density was $\sim 1.13 \times 10^{18}$ cm^{-3} at a distance 100 μm from the Al target surface. The plasma density reduced to 0.55×10^{18} cm^{-3} at 1200 μm away from the surface. The plasma temperature at the target surface was measured to be ~1.17 eV and increased to 4.2 eV at a distance of 500 μm then decreased beyond this point. Up to Al^{+3} ions were observed in their experiments [10]. An Nd:YAG laser operating at 532 nm with 3 ns pulse duration and a maximum pulse energy of 170 mJ was previously used to ablate carbon plasma, creating in excess of 70% ionization [11]. Nassissi et al., developed a laser MCI source based on excimer laser and conducted extensive studies on the characteristics of the MCI produced [12–14]. Using time-of-flight measurement of ions extracted from Cu laser plasma ablated using a

* Corresponding author. Tel.: +1 (757)269 5645.
E-mail address: helsayed@odu.edu (H.E. Elsayed-Ali).

http://dx.doi.org/10.1016/j.nimb.2015.04.066
0168-583X/

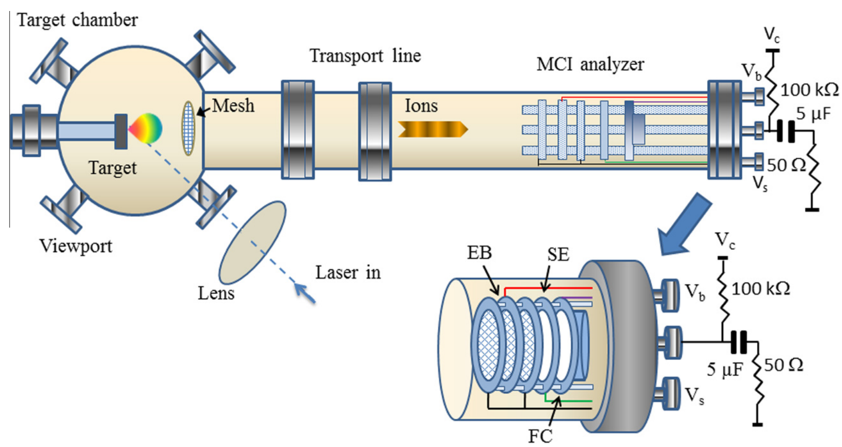

Fig. 1. A schematic of the laser multicharged ion source showing the target chamber and the electrostatic time-of-flight energy analyzer, EB: the electrostatic barrier, SE: suppressor electrode, and FC: Faraday cup.

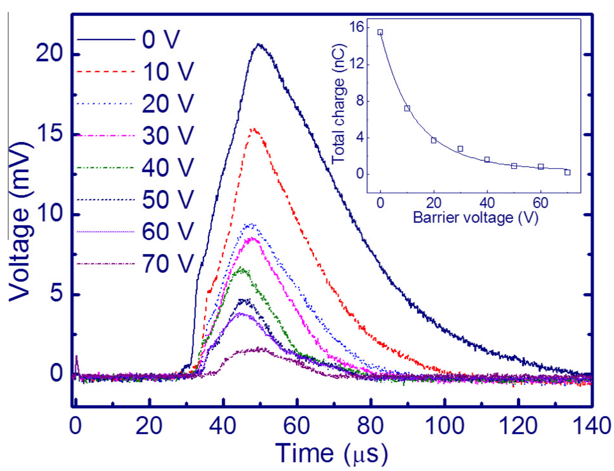

Fig. 2. Dependence of the generated multicharged ions on barrier voltage when no accelerating voltage is applied. Inset shows the reduction of total charge with the increase of barrier voltage when no accelerating voltage is applied to the target.

70 mJ pulse (3.5×10^8 W/cm^2); the ion spectra showed signals of Cu ions up to Cu^{+5}, with the vast majority of ions singly and doubly ionized with the ionization of the plasma estimated to be 16% [12,13]. A device for acceleration of laser-generated Cu MCI up to 160 keV per charge state was described [14]. Using femtosecond laser ablation, Gordienko et al., reported the generation of up to Si^{+12} ions for a laser intensity of 3×10^{16} W/cm^2 [9]. An iodine laser of λ = 1.315 μm, pulse energy of ~45 J and pulse length of ~300–700 ps irradiated on an Ag target with a laser intensity of 10^{14} W/cm^2 produces a maximum charge state of Ag^{+37} [15]. A picosecond pulsed laser operating in the range of 10^{16}–10^{20} W/cm^2 was used to irradiate metallic foils generating MCIs in the MeV energy range [16]. Yeates et al., developed a laser ion source from a Q-switched ruby laser (pulse width ~35 ns, wavelength λ = 694 nm) with a laser intensity of 10^8–10^{11} W/cm^2 and reported charge state up to Cu^{+6} [17].

Aluminum ion implantation and deposition have many applications. For example, Al ion implantation followed by oxidation was used to reduce atomic oxygen degradation of polymers [18]. Increased conductivity of ZnO by Al ion implantation was reported to be due to the reduced effects of oxygen vacancies [19]. Al ion implantation of surgical AZ31 and AZ91 magnesium alloys was used to increase their corrosion resistance [20,21]. Plasma immersion ion implantation of Al on HfO_2 causes a reduction in the leakage current, smaller flatband shift, and steep transition from the accumulation to the depletion region in the *C–V* characteristics, indicating the reduction of both bulk oxide and interface traps [22]. All of these applications were conducted with singly-charged Al ions. MCIs potentially can offer advantages due to control on both their kinetic and potential energy. The availability of MCIs with different charge states makes it possible to control the implanted ion depth profile producing uniform concentration gradient, or a tailored gradient when needed. An example where a uniform Al concentration gradient is needed is in the p-type doping of SiC by ion implantation. To achieve this uniform concentration, implantation is conducted with singly-charged Al ions with different energies ranging from 25 to 300 keV [23]. SiC is an attractive material for high power and high temperature fast devices because of its high thermal conductivity, large electron saturation drift velocity, high electric field breakdown and thermal stability [24,25]. Using an ion beam containing Al MCIs could enable implantation at different depths in a one-step process. Also, the ability to control both kinetic and potential energy of the Al ions could conceivably be used to minimize implantation damage by ion recoil. The higher charge states also reduce the required potential to reach a certain kinetic energy, thus, reducing the requirement on the high voltage power supplies and allowing development of a compact and cost-effective implanter.

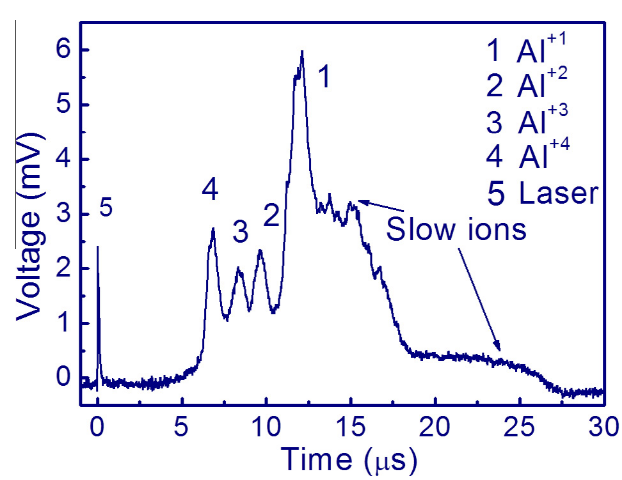

Fig. 3. Generation of Al multicharged ions for 5 kV accelerating voltage with a laser pulse energy of 90 mJ shows charge state up to Al^{+4}.