Highly Charged Ion Beams from the Tokyo EBIT for Applications to Nano-Science and -Technology

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Abstract. We report present status of a beam line for transportation of highly charged ions (HCIs) extracted from the Tokyo EBIT. We have produced continuous beams of $2.5 \times 10^5$ cps for Xe$^{44+}$ through a 1 mm aperture. With slightly high energy operation (electron beam energy: 78 keV) of the Tokyo EBIT, we have also obtained $10^3$ ions/pulse for Ta$^{70+}$ HCIs extracted by a pulse mode (trapping time: 3 sec). We are going to apply such HCI beams to nano-processes on solid surfaces by utilizing some useful characteristics of the HCI-interactions. Future perspective of HCI-based nano-science and -technology is presented.

INTRODUCTION

One of the interesting features of highly charged ions (HCIs) is that a HCI has the huge potential energy. The potential energy is equal to the summation of ionization energy to produce the HCI concerned and increases rapidly with the ion charge. For example, potential energy of Xe$^{44+}$ reaches 48 keV while singly charged Xe ion has only 12 eV of potential energy. Another feature is that the HCI has a large number of unoccupied orbitals. When a HCI approaches to a solid surface, the HCI captures a lot of electrons to the orbitals and releases the large potential energy with in a short time (<100 fs) onto a small region of the surface. Such interactions of the HCI with the surface give two important characteristics; one is a high yield of secondary electron emission and the other is terawatts power flux deposition onto a nano region.

The yield of secondary electron emission by a HCI is over hundred times larger than that by a singly charged ion at low energy collisions on the solid surfaces. The HCI captures many electrons into the high Rydberg orbitals and then emits the electrons via Auger decay processes, which repeats many times until the HCI becomes neutralized. As a result, secondary electrons more than a value of ion charge emerge from the surface to vacuum. For example Xe$^{44+}$ can emit over 100 electrons from a gold surface [1].

A nanoscopically modified HOPG (highly oriented pyrolytic graphite) surface by Xe$^{22+}$ impact is shown in Fig. 1. This image was obtained by using a scanning tunneling microscope (STM). Such surface modification results from deposition of huge potential energy of HCIs to a nanometer sized region of the surface within a
short time, which corresponds to a power flux density of 1 TW/cm². Although terawatt power density is also achieved with a short pulsed laser, the laser beam waist is about 500 nm in diameter at least. While HCIs can deposit terawatts power flux onto a nano-region.

We are going to apply HCI-interactions to nano-processes on the solid surface by utilizing two characteristics as mentioned above. The high yield property is useful for detection of collision events of HCIs with surfaces, which is applied to a single ion implantation technique. While terawatts power flux deposition causes nano-structure formation. In order to perform the HCI based nano-processes efficiently, HCI beams having high flux density are required. Therefore HCIs have to be efficiently extracted from a ion source and transported in a beam line with well-designed ion optical elements. In what follows, we show present status of a beam line constructed with the Tokyo EBIT [2, 3]; an electron beam ion trap at the University of Electro-Communications. We show then schematically a single ion implantation setup and propose some selected candidates for target materials. Finally, in addition to the HCI based nanotechnology, we describe some plans of basic nano-surface experiments of HCI-interactions with silicon substrates using the STM.

**HCI BEAM LINE**

Figure 2 shows a layout of a beam line for transportation of HCIs extracted from the Tokyo EBIT. The HCIs emerging vertically from the ion source were rectangularly deflected by an electrostatic bender and then focused onto an entrance slit of an analyzing magnet by using several electrostatic lenses and a set of the deflectors. The magnet selected the HCIs with the desired charge-to-mass ratio and focused them onto an exit slit. They were then transported to a collision chamber and impacted into a target material. Two collision chambers were installed along the beam line; one was connected with a chamber for scanning probe microscope experiments, while the other

FIGURE 1. Scanning tunneling microscope (STM) image of a Xe²²⁺ HCIs impact site on a HOPG surface.
FIGURE 2. Layout of beam line for transportation of HCIs extracted from the Tokyo-EBIT

was equipped with a reflection high-energy electron diffraction (RHEED) apparatus. The base pressures of the beam line and collision chambers were $1 \times 10^{-9}$ and $1 \times 10^{-10}$ Torr, respectively, which facilitated HCI bombardments into clean and well-defined surfaces such as Si(111)-7×7 reconstructed surfaces.

Typical charge state spectrum for xenon HCI beams are shown in Fig. 3 (A). The spectrum was obtained at the second target chamber. The beam fluxes depend strongly on a number of operational parameters of the Tokyo-EBIT and of the ion-optical elements in the beam line. By adjusting these parameters we obtain presently $2.5 \times 10^5$ ions per second for Xe$^{44+}$ through a 1 mm aperture. Figure 3 (B) shows charge state spectrum of tantalum HCIs obtained with slightly high energy operation of the Tokyo

FIGURE 3. Charge state spectra of (A) xenon and (B) tantalum HCI beams. Xe HCIs were extracted with a leaky mode while Ta HCIs were with a pulsed mode. Operational parameters are summarized in Table I.
EBIT. Ta ions were injected from a metal vapor vacuum arc ion source (MEVVA) shown in Fig 2 into the EBIT and then Ta HCIs were produced by the 78 keV and 200 mA electron beam. The HCIs were extracted by a pulsed mode with 3 sec trapping time where typically $10^3$ ions/pulse for Ta$^{70+}$ HCIs were obtained. Operational parameters of the EBIT for obtaining these spectra are summarized in Table 1.

| Parameter                        | Xe HCI beams | Ta HCI beams   |
|----------------------------------|--------------|---------------|
| Electron beam energy [keV]       | 23           | 78            |
| Electron beam current [mA]       | 150          | 200           |
| Ion extraction voltage [kV]      | 3            | 3             |
| Extraction mode                  | leaky        | pulsed (3 sec duration) |
| Beam flux 2.5x10^5 cps (Xe$^{44+}$) | 10^3 ions/pulse (Ta$^{70+}$) |

**HCI BEASED NANO-PROCESS**

A high yield of secondary electron emission can be utilized for a single ion implantation (SII) technique [4], which makes it possible to detect one by one ion impact. Figure 4 shows schematically an instrument for testing a SII technique. This arrangement consists of a channel electron multiplier (CEM) for the secondary electron detection, a 100 nanometer-sized aperture and a target stage with piezo-actuator. When a single HCI passing through the narrow aperture arrives at a target surface, a burst of secondary electrons emitted from the surface are detected at the CEM. Following the detection of the ion impact, the target is moved to a next implant position using the piezo-actuator. In this way, we can perform one by one ion implantation at the desired position. With the same manner, nanoscopic impact site can be periodically arranged if the piezo-actuator is moved periodically within the 2 dimensional plane.

**FIGURE 4.** Instrument for testing a SII technique.
The SII has been also attempted using singly charged ions [5, 6]. In this case, large kinetic energy (~100 keV) is required in order to obtain a lot of secondary electrons for detection of individual ion impacts. This causes less accuracy of implanted positions inside the target materials. Figure 5 (A) shows a lateral distribution of phosphorus ions when they are normally implanted into a Si substrate. This result was obtained by a simulation with SRIM 2000 [7]. Kinetic energies of the projectiles in (a) and in (b) are 1.5 keV and 5 keV, respectively. Each image area is 20 nm × 20 nm. Roughly speaking, positional fluctuations increase linearly with increasing kinetic energy as shown in (B), where the vertical axis is $2\sigma$ ($\sigma$: standard deviation) estimated by fitting spatial distributions along the x-axis to Gaussian curves. In the case of singly charged ions, lateral fluctuation reaches several tens or more over because about 100 keV of kinetic energy is required to detect ion impacts. While, in the case of HCIs, because the secondary electron emission is induced due to potential emission, less than keV-order of kinetic energy is enough to detect each collision event. In this case spatial fluctuation is a few nm and, as a result, more precise implantation can be achieved with HCIs.

**FIGURE 5.** (A) Lateral distribution of phosphorus ions when they are normally implanted into Si substrate (simulated results). Kinetic energy of the projectiles in (a) and in (b) are 1.5 keV and 5 keV, respectively. (B) Dependence of positional fluctuation on kinetic energy of projectiles.
SELECTED CANDIDATES FOR TARGET MATERIALS

We have several candidates for target materials such as silicon, diamond, InAs/GaAs and so on. In what follows, the HCI-based nanoprocess to each material is proposed.

The SII technique is useful for one by one doping into ultra-fine silicon devices. Impurities doped by conventional ion implantation techniques are statistically distributed over substrates. When semiconductor devices are reduced to several tens nanometer, their electric properties are seriously affected by fluctuation of the number of dopant ions in individual devices [8]. The SII technique suppresses such a fluctuation by control both of number and location of dopant ions.

Schenkel et al. [9] attempt to develop solid state quantum computers with the HCI-SII technique. Using spin flips in the hyperfine structure of $^{31}\text{P}$ atoms embedded in a silicon substrate as quantum bits (qubits) is a key idea of this development. To read out quantum information, a phosphor ion should be implanted between gate electrodes which are separated several-hundred nanometers. The interval of two implanted ions is, furthermore, required to be several-ten nanometers because their wave functions have to superpose each other in two qubits operation. The HCI-SII has the greater advantage in such requirements concerned with positional resolution than the case of using singly charged ions.

Nitrogen vacancy color centers (N-V centers) which are a kind of luminescent defects in a diamond are composed of a substitutional nitrogen and a vacancy in an adjacent lattice position. They can be created, using nitrogen ion implantation followed by annealing. Because each N-V center acts as a single photon source at room temperature without photo-quenching, several research groups attempt to apply N-V diamonds to non-classical photonic devices for quantum information [10] and computation [11]. The SII technique would make it possible to produce single photon sources at desired positions on substrates.

Extensive studies on growth of self-assembled quantum dots (QDs) [12], for example InAs QDs on GaAs, have been carried out because of not only fundamental interest such as quantum size effects but also technical usages for novel optical and electrical devices. Up to date, size and density of such QDs have been controlled well with various crystal growth techniques. Recent technical issue for application to QD devices such as low threshold lasers is on how to locate QDs at desired positions and to array periodically the dots on the substrate. It is known that the QDs grow around defects and steps of substrate. Therefore we expect that periodically arranged HCI impact sites play role as nucleation sites for QD-array growth.

ATOMICALLY RESOLVED OBSERVATION OF IMPACT SITES

As shown in Fig. 1, impact sites of HClIs can be observed with atomic resolution by using the STM if clean, well defined surfaces can be prepared. So far several groups have performed such STM observations of impact sites on HOPG (see [13] and
references therein) and mica [14] surfaces. Hamza et al. [15] have observed $^{44}$Xe$^{4+}$ impact sites on Si surfaces as craters by using an atomic force microscope with a few nanometer resolution. However impact sites on silicon have never been observed with atomic resolution although one can prepare clean, well defined surfaces, Si (111)-7×7 and Si (100)-2×1 reconstructed surfaces, under the ultra high vacuum condition. Therefore we are going to observe atomically resolved impact sites of Si irradiated with HCIs. We take interest in the following things:

(a) Differences of impact sites between Si (111) and Si (100): In the case of $\text{Ar}^+$, impact sites on Si(111) are 6 times larger than those on Si (100) due to difference of atomic binding energy between these reconstructed surfaces [16].

(b) Structure of impact sites on modified Si surfaces: Kuroki et al. [17] have reported that sputtering yields of protons from hydrogen terminated Si (100) irradiated $\text{Xe}^{n+}$ is proportional to $q^5$. STM observation can confirm directly these results with high spatial resolution.

(c) Dependence of impact site on electrical conductivity of Si substrates: Sputtering yields and mechanisms are thought to be quite different in the HCI-irradiation on metal, semiconductor and insulator [18]. We will investigate the conductivity-dependent surface modifications with one species, i.e., a silicon target, with various different concentrations of dopant ions.

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