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A modification of the laser detonation-type hyperthermal oxygen atom beam source for a long-term operation

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It has been an impedimental problem, for the laser detonation-type atom beam generator, that a poppet in the pulsed supersonic valve is rapidly eroded by the irradiation of powerful laser light and high temperature plasma. In order to operate the atom beam source for a long duration, a modification was made to hide the poppet from direct irradiation of laser and plasma. The alteration of device configuration resulted in great improvement in endurance of poppet more than 300 000 repetitions. Morphology of a polyimide film exposed to approximately 200 000 pulses of hyperthermal oxygen atom beam showed a shaglike carpet structure, which is a characteristic to that exposed to energetic oxygen atoms. A flux of the oxygen atom beam was estimated to be 5×10^{14} atoms/cm^2/pulse at a location of 30 cm away from the nozzle throat. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2957613]

I. INTRODUCTION

The laser detonation-type oxygen atom beam source using a laser-induced detonation phenomenon was originally invented by Physical Sciences, Inc. (PSI) in order to simulate 5 eV oxygen atom reactions with materials in low Earth orbit (the altitude of 200–700 km).[1] PSI's beam source can generate pulsed oxygen atom beam with a velocity of $\sim$8 km/s and fluxes of approximately $\sim10^{15}$ atom/cm^2/pulse on a large area ($\sim$1000 cm^2) exposure. The beam source also generates other energetic neutral atoms (rare gas, C, F, N, S, Cl, etc.) and molecules (O_x, C_xH_x, C_xO_x, N_xO_x, etc.) beams by selecting source gases (for example, hyperthermal oxygen atom beam is generated using oxygen molecule as a source gas). Because of unique properties of the beam source, the hyperthermal neutral atom beams have also been used to investigate fundamental gas-gas[2] and gas-surface[3] chemical reactions, and surface fabrications.[4–6]

Erosion of a poppet used in a pulsed supersonic valve (PSV) occurs during long-term operation with more than several hundred thousands of pulses. This deterioration was caused by high power laser irradiation and/or by exposure to high temperature laser plasma. The erosion of poppet leads to gas leakage, and hence the continuation of operation becomes unable.

In this study, we have modified the laser detonation-type oxygen atom beam source for obtaining long-term operation. In order to prevent the erosion of the poppet, we designed an axis of the PSV so as to be near perpendicular to that of a high power laser light. Time of flight (TOF) measurement system using a quadrupole mass spectrometer (QMS) characterized a hyperthermal oxygen atom beam generated from this modified oxygen atom beam source. Flux of hyperthermal oxygen atom beam was estimated using an etching depth of polyimide film.[4]

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II. ORIGINAL LASER DETONATION-TYPE OXYGEN ATOM BEAM SOURCE

A schematic of an original laser detonation-type hyperthermal oxygen atom beam source is shown in Fig. 1.[1,4,7] Figure 1(a) shows the configuration of the original beam and the principle of generating hyperthermal neutral oxygen atoms. A solenoid-type PSV is usually used to inject source gas into the nozzle. In PSV, a poppet made of polytetrafluoroethylene (PTFE) is installed. The PSV is attached at the bottom of the nozzle throat, and therefore the axes of the PSV and the nozzle are identical. Figure 1(b) indicates a burst of source gas through an orifice with a diameter of 1 mm during the poppet opening. When the density of source gas in the nozzle is high enough to create laser plasma, a high power transversely excited atmospheric (TEA) CO_2 laser (typically 5 J/pulse) is fired and the laser light is focused at the nozzle throat [Fig. 1(c)]. The axes of the laser light and the PSV have almost the same incidence. The focused laser light causes a laser detonation of a part of the source gas in the focal point and creates the laser plasma with high temperature, as shown in Fig. 1(d). Once laser plasma is formed, infrared laser light is absorbed to the plasma, causing the expansion of the laser plasma through the nozzle. The laser plasma grows along the axis of the laser light and the source gas is atomized by the laser plasma. After the laser irradiation stops, electron-ion recombination occurs but atomic recombination does not. As the gas expands, its temperature and density decreases, whereas its velocity increases. As mention below, a nonaccelerated composition (thermal composition) of introduced source gas is detected, implying that the poppet still opens after the plasma formation.

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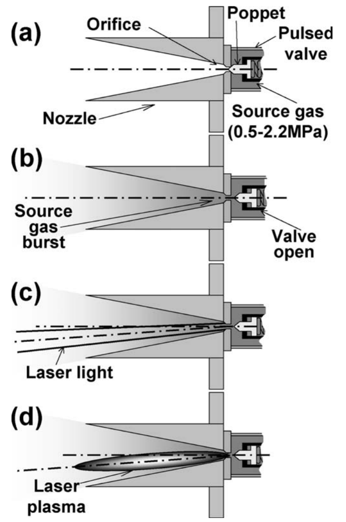

FIG. 1. Principles and configurations of the original laser detonation-type hyperhermal oxygen atom source, (a) detailed configuration of the source, (b) burst of source gas as the poppet opens, and (c) emission of high power laser light by the CO_2 TEA laser. The axis of the laser light is almost the same as that of the PSV. The detonation point is the bottom of the nozzle, where the poppet is placed, and (d) the formation of laser plasma along the axis of the laser light by the laser power.

It is noted that the poppet, in the configuration of the original atom beam source, is exposed to the high power laser light and high temperature plasma. The erosion of poppet is mitigated by the plasma which adsorbs the infrared laser light as well as by the residual source gas existing near the nozzle throat. Thus it appears that the poppet erosion is prevented by increasing the amount of source gas. However, this leads to an inverse effect of decreasing the velocity of atom beam. Therefore, to obtain high velocity atom beam, an introduction of the increased amount of source gas is limited.

Figure 2 shows the photographs of poppets. The unused poppet indicated in Fig. 2(a) shows a clear conical shape. A poppet subjected to opening and closing for about 50 000 cycles without the laser firing is shown in Fig. 2(b). The apex is deformed mechanically by a contact with the orifice of the PSV. However, there was no gas leakage. Figure 2(c) shows the damaged poppet by the laser plasma after operating 3000 cycles. The apex of the poppet disappeared,

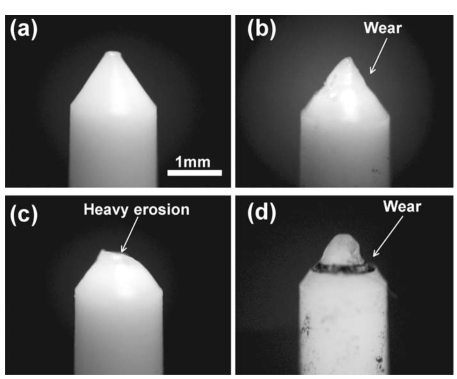

FIG. 2. Photographs of (a) the new poppet, (b) the poppet after 50 000 of opening and closing without the laser firing, (c) the puppet after approximately 3000 pulses with laser firing in the original beam source, and (d) the poppet after approximately 300 000 pulses of laser firing with the modified beam source.

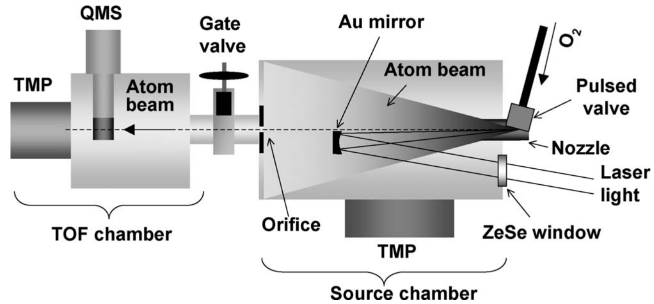

FIG. 3. Schematic drawing of the modified laser detonation-type atom beam source in this study.

and consequently the leakage of gas occurred. Generally, endurance of poppet with the laser fire is approximately 10 000–20 000 cycles. Figure 2(d) will be discussed later.

III. MODIFIED LASER DETONATION-TYPE OXYGEN ATOM BEAM SOURCE

Figure 3 schematically presents the modified hyperthermal atom beam source facility. This system consists of a source chamber and a TOF chamber. These chambers were evacuated by a 5000 l/s turbo molecular pump and a 500 l/s turbo molecular pump, respectively. The vacuum pressures of each chamber are 10^{-5} and 10^{-7} Pa, respectively. The two chambers are connected by a UHV valve. The source chamber consists of a copper nozzle, a PSV, and a concave Au mirror to generate neutral atom beams. A CO_2 TEA laser (not shown in the Fig. 3) with pulse energy in a range from 4 to 6 J/pulse is used to form laser plasma. The Au mirror with a diameter of 6 cm is located away from the atom beam axis, i.e., the center of the Au mirror is approximately 3.5 cm off from the atom beam axis. A laser light is introduced in the source chamber through a ZeSe window and then focused at the bottom of the nozzle throat by the concave Au mirror (50 cm in focal length for the laser light). Atom beam is collimated with the use of a 100 mm^2 orifice placed at 80 cm from the apex of the nozzle throat, and then the atom beam enters the TOF chamber. The QMS is equipped with the TOF chamber, and the distance between the nozzle throat and an ionizer of the QMS, i.e., flight length of atom beam, is 2.08 m. The composition and velocity of atom beams were monitored by the TOF measurement system using the QMS. Atoms and molecules are ionized in an ionizer, and then the ions reach a channeltron in the QMS. TOF distributions involve the flight time of ion from the ionizer to the channelton. The ion flight time (t_{ion}) is proportional to the square root of its mass (m), i.e., $t_{ion}=\alpha(m/e)^{1/2}$ (where α is a constant),[4] because all the ions are accelerated by the same potential difference between the ionizer and the channeltron. From the TOF data of free expanded argon, neon, and helium gases, α is calculated to be 8.38 in this system.

Details of the nozzle configuration in the modified hyperthermal atom beam source are shown in Fig. 4. Note that the PSV inclines with respect to the laser light axis and that the poppet is hidden from both the laser light and the laser plasma. Therefore, there is almost no possibility that the

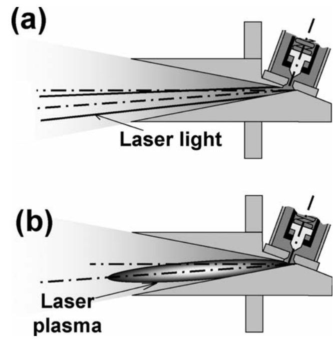

FIG. 4. Detailed layout of the modified oxygen atom source around the nozzle. The axis of the PSV is near perpendicular to that of the laser light. (a) and (b) show no direct irradiation of laser light and laser plasma, respectively.

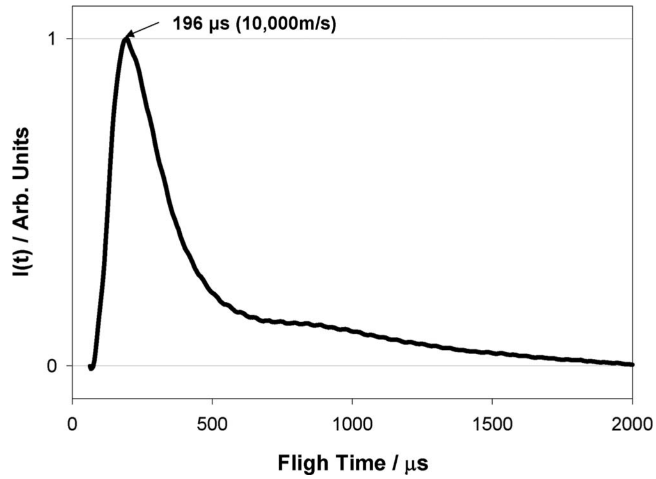

FIG. 6. Flux distribution, $I(t)$, at $m/q=16$ as a function of flight time. Flight time zero is the time at the laser firing.

laser light irradiates directly the poppet and the laser plasma erodes the poppet. The modification was quite effective in protecting the poppet. Figure 2(d) is the photograph of a poppet after the operation of approximately 300 000 pulses with the laser firing in the modified beam source. The poppet still has the apex. Although mechanical deformation is visible on the ridge line. Consequently, no gas leakage was detected.

Mass charge ratios (m/q) of 16 and 32, which correspond to oxygen atoms and molecules, are detected using oxygen molecules as source gas. Figure 5 represents TOF distributions, $N(t)$, at $m/q=16$ (oxygen atoms) and $m/q=32$ (oxygen molecules), in gray and black lines, respectively. These signals were detected only when the ionizer was turned on, indicating that no ion components exist in the beam. The TOF distributions include the laser delay and the ion flight time, thus, time zero does not correspond to the time zero in flight time in Fig. 5. In the $m/q=32$ distribution, a peak at approximately 2600 μs comes from a thermal component that is not accelerated and atomized by the laser plasma. In the $m/q=16$ distribution, the peak at 2600 μs which corresponds to a component of cracked O^+ from oxygen molecules in the ionizer is also recognized. A peak of the $m/q=16$ distribution at 630 μs comes from a hyperthermal component accelerated and atomized by the laser plasma. A small peak of the $m/q=32$ distribution at the hyperthermal region exists. In contrast to the modified beam source, the original laser detonation-type sources produce hyperthermal oxygen molecule components. We previously developed a laser detonation-type oxygen atom source in which an axis of a laser light is perpendicular to that of a burst of source gas, and found that the developed source had no hyperthermal oxygen molecule component.[8] The results indicating a little hyperthermal oxygen molecule component are characteristic to the laser detonation-type sources in which an axis of a laser light is near perpendicular to that of a burst of source gas. Figure 6 shows a flux distribution, $I(t)$, at $m/q=16$ as a function of flight time, converted from the $m/q=16$ distribution in Fig. 5. In Fig. 6, we subtracted cracked O^+ component from oxygen molecules and applied the relationship of $I(t) \propto N(t)/t$ by taking into account the residence time in the ionizer.[4] The flight time in Fig. 6 is compensated by subtracting the laser delay and the ion flight time. The flux distribution, $I(t)$, of the oxygen atom component has a broad

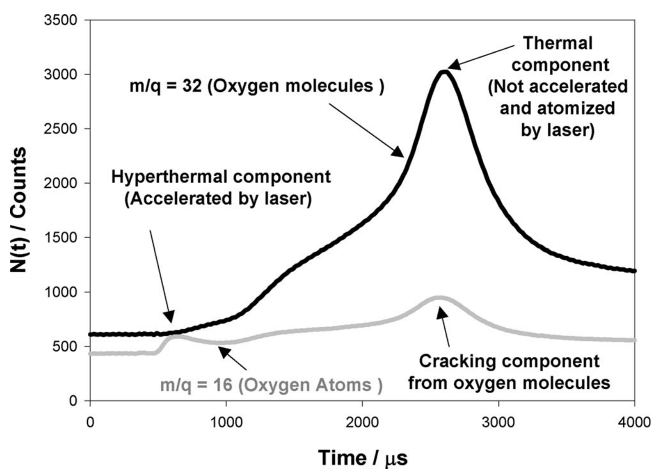

FIG. 5. TOF distributions, $N(t)$, at $m/q=16$ (gray line) and $m/q=32$ (black line). The TOF distributions include the laser delay time and the ion flight time.

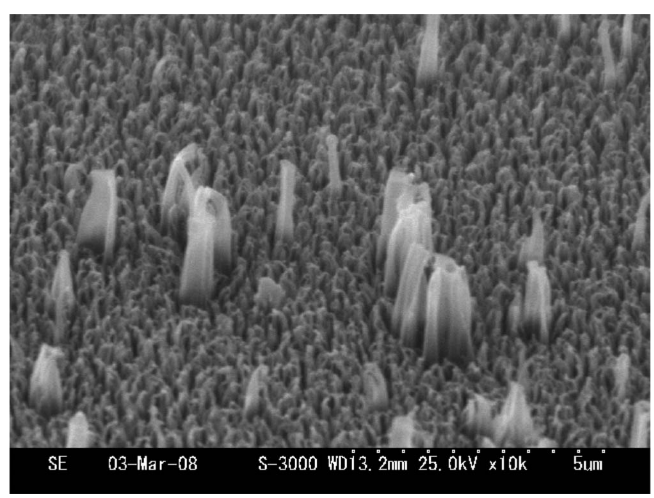

FIG. 7. Polyimide film exposed to oxygen atom beam after 200 000 pulses. Shaglike carpet structure is obvious.

distribution. The peak at 196 μs is correspondent to a velocity of approximately 10 000 m/s.

Polyimide film was exposed to the hyperthermal oxygen atom beam generated by the modified laser detonation-type oxygen atom beam source with the same operating conditions as those of the TOF distributions shown in Fig. 5. Scanning electron microscopy image of the polyimide film exposed to approximately 200 000 pulses is shown in Fig. 7. Shaglike carpet structure, which is commonly observed for the polyimide film exposed to energetic oxygen atoms,[9] is obvious. We estimated a flux of oxygen atoms in the beam from an etching depth of polyimide film,[4] and the estimated flux was approximately 5×10^{14} atoms/cm^2/pulse at 30 cm from the nozzle throat. This value is equivalent to that reported in previous articles.[1,7]

In summary, a simple but effective modification of nozzle configuration of hyperthermal atom beam source provided a long-term operation without substantial difference not only in velocity but also in flux as compared with the original atom beam source. The endurance of poppet is at least more than ten times.

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