Quantitative measurements of light-induced desorption of rubidium atoms from quartz substrates

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We investigated the light-induced desorption (LID) of Rb atoms from quartz substrates to understand better the LID observed in alkali-metal vapor cells used in laser cooling experiments. The substrate was first exposed to Rb under ultrahigh vacuum conditions. The Rb was found to diffuse into the substrate by x-ray photoelectron spectroscopy. Rb atoms were then deposited with a density of $\sim 10^{15}$ atoms/cm^2 on the surface, from which LID was observed upon irradiation by ultraviolet light. The LID rate depended linearly on the light intensity in the investigated range up to 15 mW/cm^2. A typical value was 10^{10} atoms/(s cm^2) per mW/cm^2 at a photon energy of 4.3 eV (290 nm in wavelength). We found that the LID rate increased with photon energy in the range 1.8–4.3 eV (700–290 nm in wavelength).

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I. INTRODUCTION

Alkali-metal vapor cells are workhorses in many atomic physics experiments, such as precision spectroscopy, optical pumping, and laser cooling and trapping. A substantial increase in atomic vapor density was first observed when a Na vapor cell coated with polydimethylsiloxane (PDMS) was irradiated with light [1]. This was the result of atomic desorption from the PDMS coating and was referred to as "light-induced atom desorption" (LIAD). Since then, light-induced desorption (LID) of alkali-metal atoms has been found from various types of coatings (siloxane and paraffin) [2–6]. Desorption has also been observed in laser cooling experiments when uncoated cell surfaces, such as glass (quartz, Pyrex, and Vycor) [7–15] and metal (stainless steel and aluminum) [12,16] were irradiated with light. This desorption turned out to be very useful for loading cells quickly on demand. The LIAD from glass surfaces covered with a superfluid helium film was also used for loading sealed cells at liquid helium temperatures [17]. Recently, porous materials, such as porous silica and alumina, have been studied in the context of LIAD [18,19]. All of these desorption types observed in alkali-metal vapor cells are commonly called LIAD. However, it is still not clear which elementary processes occur and whether there is a common mechanism in these phenomena.

To address these problems, we first studied the LIAD from the bare glass of ultrahigh vacuum (UHV) cells used in laser cooling experiments. This system should be relatively simple, as it consists of an uncoated, clean glass surface and low-density alkali-metal adsorbates only. A prior study [12] showed that the desorption efficiency increased with increasing photon energy. The other quantitative properties of LIAD, however, have not been well investigated. Although there are some theoretical predictions of elementary desorption processes, as reviewed in Ref. [20], quantitative experimental characterization of the surface conditions and the desorption of alkali-metal vapor cells is necessary.

Here, we report the LID of Rb atoms deposited on bare quartz substrates in a UHV chamber at room temperature. Quartz was chosen because it is a simple glass composed of only Si and O. Some have reported that quartz was not suitable for LIAD [8], but others have used it to load cells by LIAD for a magneto-optical trap (MOTs) [13]. We found that it was necessary to expose the substrate to Rb for some time before we could observe LID. A typical desorption rate was 10^{11} atoms/(s cm^2) when we deposited Rb with a density of 10^{15} atoms/cm^2 (about 10 monolayer equivalents) and irradiated the substrate with ultraviolet light (intensity: 10 mW/cm^2) at a photon energy of 4.3 eV (wavelength $\lambda =$ 290 nm). The LID rate increased with photon energy between 1.8 and 4.3 eV ($\lambda =$ 700–290 nm), consistent with previous measurements of a MOT [12]. The surface analysis performed after the substrates were taken out of the experimental chamber revealed that they were contaminated mainly by C at the surfaces and were penetrated by Rb.

This paper is organized as follows. We first explain the experimental method in Sec. II. This is followed in Sec. III by experimental results for both surface analysis and desorption measurements. We also present some speculation on the surface conditions. The paper concludes with Sec. IV.

II. EXPERIMENT

The experimental setup is shown schematically in Fig. 1. The substrates were synthetic quartz (ES grade, TOSOH Corp.) containing impurities (Al, Ca, Cu, Fe, Na, K, Li, and Mg), nominally of less than 0.1 ppm each, except for OH (1000 ppm). The surface roughness was measured to be 0.5 nm in root mean square with an atomic force microscope. The dimensions of the substrates were 20 mm in diameter and 0.5 mm in thickness. The substrate was supersonically cleaned with methanol, acetone, and distilled water and then introduced into an experimental chamber. The temperature of the substrate, measured with a thermocouple touching the surface, was controlled by a resistive heater [pyrolytic-graphite–pyrolytic-boron-nitride (PG/PBN) heater, Momentive Performance Materials Japan LLC] and liquid nitrogen (LN2). The substrate and chamber were baked at 200 °C for a few tens of hours. The base pressure of the chamber reached 2×10^{-7} Pa using an oil-free pumping system (dry scroll, turbomolecular, and ion pumps) after baking. Rb atoms were deposited on the substrate from an alkali-metal dispenser (RB/NF/3.4/12 FT10+10, SAES

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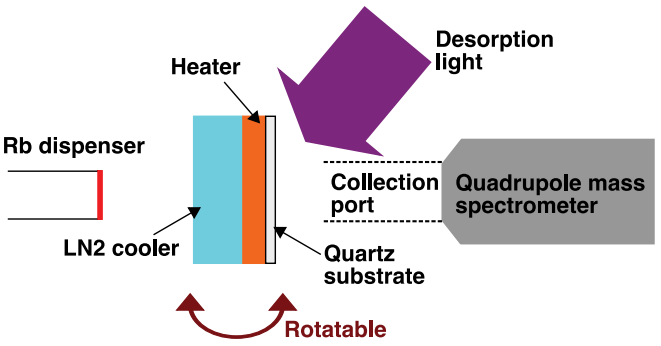

FIG. 1. (Color online) Schematic of the experimental setup. The quartz substrate is rotatable to face either the Rb dispenser or the quadrupole mass spectrometer (QMS). The collection port is used only when we check whether detected signals originate from atoms desorbing from the quartz substrate.

Getters S.p.A.). After the termination of Rb deposition, the substrate was turned around to face toward a quadrupole mass spectrometer (M-201QA-TDM, Canon Anelva Corp.). It was then irradiated with light to induce desorption, and the desorbed atoms were detected with this QMS. A collection port that made the QMS "see" only the substrate was attached to the QMS when we checked whether observed atoms were really desorbed from the quartz substrate. The data shown in this paper were taken without the collection port because the QMS with the collection port had to be located farther away from the substrate, reducing the signal. We used a 300 W xenon lamp (MAX-302, Asahi Spectra Co., Ltd.) as a light source and selected a specific wavelength from $\lambda = 290$ to 700 nm with cold mirrors and interference filters to measure the dependence of the desorption rate on the wavelength (photon energy). The bandwidths of selected light were 10 nm for $\lambda = 290$, 330, and 380 nm, 20 nm for $\lambda = 390$ nm, and 40 nm for $\lambda = 410$, 500, 600, and 700 nm.

III. RESULTS AND DISCUSSION

We first related the QMS signal current to the desorption rate of Rb atoms by measuring the thermal desorption from a thick Rb film. The desorption rate should be balanced by the intensity of atoms impinging on the film if the film is in a saturated Rb vapor. We calculated this rate to be 2×10^{13} atoms/(s cm^2) at 15 °C from the known saturated vapor density [21] and compared it with the QMS current measured at the same temperature. The thick film was formed by depositing Rb atoms on the substrate held at −50 °C. The film was thick enough to be visible with the naked eye. We inferred that its surface density was of the order 10^{17} atoms/cm^2 from the integrated signal of the thermally desorbing atoms measured during gradual heating of the substrate from −50 °C. Note that we assumed the density of the Rb monolayer to be about 4×10^{14} atoms/cm^2 from the known nearest-neighbor distance of Rb metal [22]. We considered that the overall uncertainty in the desorption rate was around a factor of 3.

LIAD signals were observed after the substrates were first exposed to Rb. We consider that this stage corresponds to "curing" [23,24], during which Rb atoms are supposed to react

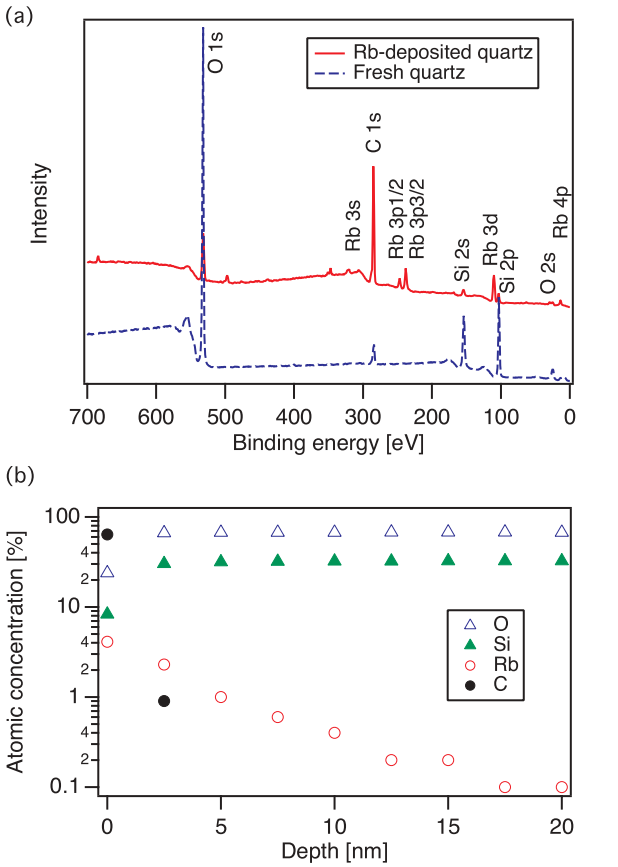

FIG. 2. (Color online) (a) Wide scanning spectra of x-ray photoelectron spectroscopy for a Rb-deposited quartz substrate and a fresh quartz substrate. The spectrum curves have arbitrary offsets for better display. Some major peaks are labeled by their originating atomic levels. (b) Depth profile for major elements observed at the surface of the Rb-deposited quartz substrate. The carbon signals are below a detectable level over 5 nm in depth.

with active surface sites and remain bound there. We found by x-ray photoelectron spectroscopy (XPS) that Rb atoms even penetrated into the quartz substrates, which we describe below.

We performed XPS surface analysis for substrates taken out of the experimental chamber after LIAD measurements. Although minimized, the exposure of the substrates to air was unavoidable. Figure 2(a) shows a typical wide scanning spectrum measured for a used (Rb-deposited) substrate that had not been heated over 200 °C together with one for an unused fresh quartz substrate. It can be seen clearly that the used substrate was contaminated by various elements, in addition to the intentionally deposited Rb. Although the origins of all contaminants were not clear, C, the most notable, is known to be common on surfaces in ultrahigh vacuum chambers [25]. Detailed scanning spectra (not shown) indicated that most C atoms had formed C-C and C-H chemical bonds.

Figure 2(b) shows the depth profile measured by XPS during sputtering of the used substrate with Ar^+ ions. As the sputtering continued, the C contamination rapidly disappeared, and the main glass components of Si and O reached the

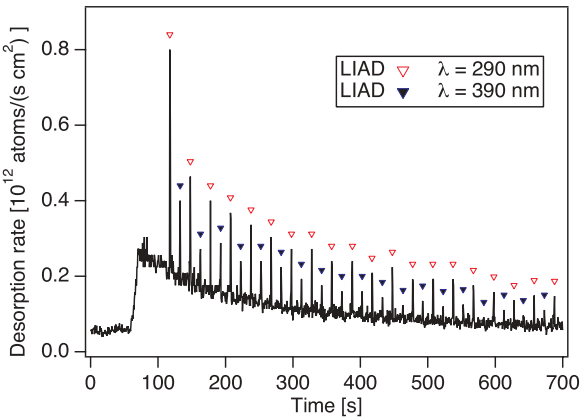

FIG. 3. (Color online) The LIAD signal obtained by irradiating two desorption lights with wavelengths $\lambda = 290$ and 390 nm alternately. The light was turned on for 1 s every 15 s, producing a distinct increase in the QMS current due to LIAD. The light intensity was 15 mW/cm^2.

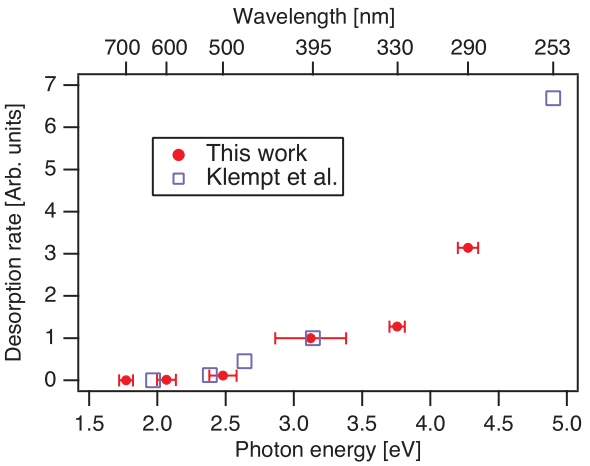

FIG. 4. (Color online) Relative desorption rate as a function of photon energy or light wavelength. The error bars represent the bandwidths of the selected photon energies. The desorption rate at 3.1 eV with a relatively large error bar was the average of results for desorption lights with $\lambda = 380$, 390, and 410 nm. Data taken from a previous report [12] are also plotted for comparison. For both data sets, the rates are normalized to those at 3.1 eV.

stoichiometric ratio 1:2. However, the slow decrease in Rb atomic concentration indicated that Rb diffused into the quartz. We considered this to be one of the results of the curing [24].

We deposited the Rb atoms on cured surfaces at room temperature to observe LIAD. Most of the atoms incident on the surface were not stuck, compared with substrates held at $-50\,^{\circ}$C. The surface densities of Rb atoms deposited on the substrates were inferred by heating the substrate to 600 °C at a constant rate of 7 °C/s and measuring the thermally desorbed atoms. This method is the so-called temperature programed desorption (TPD). We observed a broad desorption peak at about 300 °C. We estimated that this peak corresponded to a deposition amount of the order 10^{15} atoms/cm^2, or about 10 monolayer equivalents. We found that when the substrate was heated much higher than 200 °C, the adsorption and desorption behavior of Rb changed substantially. We therefore performed the TPD measurement only once for each sample at the end of a series of measurements. This is a reason that we were only able to make a rough estimate of the amount of deposited atoms.

We irradiated the Rb-deposited surfaces with light and observed the LIAD. Figure 3 shows some typical data. After the deposition was finished, a residual background Rb vapor was detected from time $t = 0$ to 60 s, after which the substrate faced toward the QMS. The signal then increased due to the thermally desorbing atoms, which were bound to the substrate surface at relatively low adsorption energy. This signal originating from the thermal desorption decreased with time, with a time constant of the order 100 s. From $t = 117$ s, we irradiated the whole area of the substrate with light pulses (duration: 1 s), alternately using $\lambda = 290$ and 390 nm every 15 s. This low duty minimized the heating of the substrate by light. The light power was 50 mW in both cases. Desorption peaks appeared and disappeared immediately when the light was turned on and off, respectively. The first peak corresponded to an increment in the desorption rate of 6×10^{11} atoms/(s cm^2). The peak height decreased with repeated irradiation. The LIAD signal was observed even after the thermal desorption fell below a detectable level. The LIAD rate decreased typically by a factor of 3 over 5 h without light illumination after the termination of Rb deposition.

We observed that the desorption rate depended almost linearly on the light intensity. A typical rate was 10^{10} atoms/(s cm^2) per mW/cm^2 at a photon energy of 3.4 eV ($\lambda = 290$ nm) when the substrate was irradiated soon after the Rb deposition.

As seen in Fig. 3, the desorption rate is higher at higher photon energy. The relative dependence of the desorption rate on the photon energy is shown in Fig. 4, where the rate at 3.1 eV is set to be unity. To eliminate variation in the desorption rate between experiments, we compared the rates at different pairs of photon energies in the same manner as shown in Fig. 3. We also normalized the desorption rate by the number of photons. The observed monotonic increase in the desorption rate with increasing photon energy in the range of 1.8 to 4.3 eV ($\lambda = 700$–290 nm) is consistent with the previous result of LIAD loading rates of a Rb MOT measured by Klempt *et al.* [12]. Their data, normalized in the same way as described above, are also plotted in Fig. 4.

Finally, we speculated on the surface conditions of quartz substrates from which we observed the LID of Rb atoms. The fact that the LIAD became active after the curing process suggested that the Rb atoms that optically desorbed were not strongly bound to the surface because the active bonding sites of the surface should be passivated during the curing process. This speculation is supported by the fact that the LIAD rate decreased with a time constant of about 5 h; the atoms may leave the surface thermally. Metallic aggregates probably formed on the Rb-deposited surface, in view of the surface density of 10^{15} atoms/cm^2 [26]. We cannot exclude the possibility that surface impurities like hydrocarbons affected the LIAD.

IV. CONCLUSIONS

To understand the LIAD observed in alkali-metal vapor cells used in laser cooling experiments, we studied quartz surfaces that were cured by Rb and further covered with Rb at a density of 10^{15} atoms/cm^2. Rb diffused below the surface. Some contaminants, particularly C, were found on the surface. We observed the LID of Rb atoms when the surface was irradiated by ultraviolet light. The desorption rate increased with photon energy, which was consistent with the previous paper [12]. This depended almost linearly on the light intensity, which was 10^{10} atoms/(s cm^2) per mW/cm^2 at a photon energy of 4.3 eV ($\lambda = 290$ nm). Although still rough, a quantitative estimation of the surface density and the desorbing rate was made for a surface that may simulate that of laser cooling cells. Our results will be helpful to elucidate the mechanisms of LIAD observed in alkali-metal vapor cells.

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