Development of a UHV-compatible Low-energy Electron Gun using the Photoelectric Effect*

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We developed a low-energy (≤100 eV) electron gun that uses the photoelectric effect, and demonstrated its capability for the study of electronic excitation processes at the surfaces of solids. A LaB₆(100) single crystal was used as a photocathode and a laser diode (E_{photon} = 2.62 eV) was used as a light source. The electron gun was compatible with ultra-high vacuum (UHV) conditions due to its low outgassing. An energy width of 0.11 eV was obtained without an energy selector, and the maximum current was 38 nA. The energy width of the emitted electrons and the work function of the photocathode were estimated from the relation between the photoelectron energy distribution and the cathode temperature. Using the electron gun, we successfully observed the electron-stimulated desorption of metastable Ne atoms from a solid Ne surface.

1. Introduction

A conventional electron gun generates electrons from a thermionic cathode composed of high-melting-point metal (or metal-like material) such as W, Pt, Ta, or LaB₆. Thermal electrons tend to have a large energy spread that generally must be reduced using an electron energy selector. However, this considerably decreases the electron beam current. Moreover, the high-temperature cathode causes a pressure increase in the vacuum chamber, which can be a problem when studying solid surfaces.

Over the past three decades, electron sources using the photoelectric effect have been developed and widely used in accelerators. These photoelectron guns can generate electron beams with large current, low emittance, and narrow time pulses. An interesting feature is that the maximum energy of the photoelectron is determined by the difference between the incident photon energy E_{ph} and the photocathode’s work function φ. Therefore, choosing E_{ph} to be slightly larger than φ generates a photoelectron beam with a narrow energy width without needing an energy selector.

We constructed an ultra-high vacuum (UHV) compatible low-energy electron gun using LaB₆ as the photocathode and a laser diode as the light source. Single-crystal LaB₆ is suitable for photocathodes as it is readily available and chemically stable, and has a high melting point of around 2500 K. It also has a low work function of around 2.5 eV. Here, we report the details of the electron gun, the properties of the photoelectron beam, and the application of the electron gun to electron-stimulated desorption (ESD) experiments on the surface of a rare gas solid.

2. Experimental Apparatus

The apparatus is outlined in Fig. 1. Except the light source, it is contained in a vacuum chamber evacuated to 1.6×10⁻⁸ Pa using two turbo molecular pumps in tandem and a Ti sublimation pump. The chamber contains most of the components of the electron gun, a copper substrate, and a microchannel plate for measurements of time-of-flight spectra of the desorbed particles in ESD experiments (section 3.2).

The electron gun consists of a light source, a photocathode, an electron lens system, and an electron energy analyzer. The light source is a laser diode (NDA4116, NICHIA Corp.) with a photon energy E_{ph} of 2.62 eV and maximum optical output power of 120 mW. The laser is fixed on an x-y stage outside the vacuum chamber, and the laser beam is focused on the cathode surface using a convex lens with a focal length of 300 mm.

![Fig. 1 Schematic view of the experimental apparatus.](image-url)
The photocathode is a cylindrical single-crystal LaB$_6$ (100) assembly (DENKA Co., Ltd.) with a 1 mm diameter and 3 mm length. Given that the nominal work function of the LaB$_6$(100) is known to be around 2.5 eV, we expect the energy width of the photoelectrons to be less than 0.15 eV. The cathode surface is cleaned by resistive heating to 1800 K for several minutes before each experimental run.

The electron lens system consists of three acceleration lenses, a quadrupole deflector, and an einzel lens. The quadrupole deflector is installed to separate the electron beam from the incident laser beam.

A parallel-plate electron energy analyzer measures the energy distributions of the electron beam and a Faraday cup is employed as an electron detector. The analyzer is designed to have a geometric resolution of $\delta E/E = 0.005$.

3. Results and Discussion

3.1 Characteristics of the photoelectron beam

3.1.1 Time dependence of the photoelectron current

Figure 2 shows the time dependence of the photoelectron current measured at a cathode temperature of 300 K and laser power of 100 mW. The time origin begins after cathode cleaning. The initial maximum current of 38 nA decreased by half in about 100 hours and then remained almost constant. This was probably due to the adsorption of residual gas onto the cathode surface. The decreased current fully recovered upon cleaning the cathode.

We also measured the current when the cathode was ohmically heated up to 1200 K. Although the photoelectron current increased with increasing cathode temperature (maximum current 95 nA at 800 K), heating increased the energy spread of the beam. (This is discussed in detail in the following section.)

The chamber pressure obviously affected the photoelectron emission: emission was observable only for a few seconds at $10^{-6}$ Pa. We note that the pressure did not increase during photoelectron emission.

3.1.2 Photoelectron energy width

Figure 3 shows photoelectron energy spectra measured at cathode temperatures of 300 and 800 K. The photoelectron energy was 45 eV, and the geometric resolution of the analyzer was 0.23 eV. The energy width measured at 800 K was larger than that at 300 K. Figure 4 shows the increase in full width at half maximum (FWHM) of the energy distribution with increasing cathode temperature.

The measured FWHM $\Delta E_{\text{meas}}$ depends on the photoelectron energy width $\Delta E_e$ and the analyzer resolution $\delta_a$. We assumed that $\Delta E_{\text{meas}}^2$ can be estimated as the sum of the squares of $\Delta E_e$ and the analyzer resolution $\delta_a$, as follows:

$$\Delta E_{\text{meas}}^2 = \Delta E_e^2 + \delta_a^2.$$  

We estimated the dependence of $\Delta E_e$ on the cathode temperature $T$ as follows. Assuming that the photoelectron energy distribution is directly determined by the Fermi distribution function $f(E)$ as shown in Fig. 5, it corresponds to the area shaded gray in Fig. 5. Here, $f(E)$ is given as

$$f(E) = \frac{1}{\text{exp}[(E-e_f)/k_B T] + 1}.$$  

![Fig. 2](image2.png)  

**Fig. 2** Photoelectron current as a function of time measured at 300 K cathode temperature, 100 mW laser power, and $1.6 \times 10^{-4}$ Pa chamber pressure.

![Fig. 3](image3.png)  

**Fig. 3** Photoelectron energy distribution measured at cathode temperatures of 300 and 800 K. The photoelectron energy was 45 eV. The origin of the energy scale is set to the peak energy of the distribution.

![Fig. 4](image4.png)  

**Fig. 4** FWHM of the photoelectron energy distributions as a function of cathode temperature from 300 to 1200 K (solid circles). The solid and dotted lines are fitted results for photoelectron energy width $\Delta E_e$ and the FWHM $\Delta E_{\text{meas}}$, respectively. See text for details.
where $E$, $\varepsilon$, $k_b$ and $T$ are the electron energy level, the Fermi level of the cathode, the Boltzmann constant, and the temperature of the cathode, respectively. A photon of energy $E_{ph}$ can emit an electron occupying an energy level higher than $E_{min} = E_{vac} - E_{ph} = \varepsilon + \phi - E_{ph}$. Here, $E_{vac}$ and $\phi$ are the vacuum level ($\varepsilon + \phi$) and the work function of the cathode, respectively. The FWHM $\Delta E_x$ of the gray area in Fig. 5 is given by $\Delta E_x = E_{1/2} - E_{min}$. We define $E_{1/2}$ to satisfy the equation $f(E_{1/2}) = f(E_{min})/2$.

To calculate $E_{1/2}$ we introduce the inverse function $g[f(E)]$ of the Fermi distribution function $f(E)$ as follows:

$$g[f(E)] = k_b T \ln \left( \frac{1}{f(E)} - 1 \right) + \varepsilon$$  \hspace{1cm} (3)$$

$E_{1/2}$ is then given as $E_{1/2} = g[f(E_{min})/2]$. Finally, we obtain $\Delta E_x$ as

$$\Delta E_x = E_{1/2} - E_{min}$$ \hspace{1cm} (4)

$$= k_b T \ln \left[ 2 \exp \left( -\frac{E_{ph} - \phi}{k_b T} \right) + 1 \right] + E_{ph} - \phi.$$ \hspace{1cm} (5)

We fit Eqs. (1) and (5) to the experimental results in Fig. 4 with free parameters $\phi$ and $\delta_x$. Fitting results for $\Delta E_{max}$ and $\Delta E_x$ are shown in the figure as dotted and solid lines, respectively, with the fitting parameters $\phi = 2.51 \pm 0.03$ eV and $\delta_x = 0.19 \pm 0.02$ eV. Our experimental results are well reproduced by the fitting curve. The photoelectron energy width was calculated to be 0.11 eV at a cathode temperature of 300 K. The results suggest that cathode heating is a practical way of increasing the photoelectron current if the broadening of the energy width ($\leq 0.16$ eV) is acceptable.

### 3.1.3 Quantum efficiency of the electron gun

The quantum efficiency $\eta$ of the photoelectric effect is denoted as

$$\eta = \frac{I_{PE}}{e P/E_{ph}}$$ \hspace{1cm} (6)

where $I_{PE}$ is the emitted photoelectron current, $P$ the light source power, $E_{ph}$ the incident photon energy, and $e$ the elementary electric charge. Table 1 lists $\eta$ measured at cathode temperatures of 300 and 800 K under light source condition of $E_{ph} = 2.62$ eV and $P = 0.1$ W together with the results of Leblond et al.\(^2\) The quantum efficiency is known to be proportional to $(E_{ph} - \phi)^2$ at the weak electric field limit\(^4\). The results listed in Table 1 roughly follow this relation.

### 3.2 Application to electron-stimulated desorption (ESD) on rare gas solid

We performed ESD of metastable Ne atoms from a solid Ne surface using the apparatus shown in Fig. 1. Ne gas was condensed on a copper substrate, which was kept at a temperature below 6 K. The thickness of the solid Ne was 100 monolayers (ML).

Figure 6 shows the desorption yields (black points) as a function of incident electron energy\(^5\). Note that the energy shown in the figure is nominal, because the electron energy was not calibrated. There are three resonant-like peaks at 18.3, 19.0, and 20.0 eV with FWHMs of 0.3–0.5 eV. These resonant structures are attributed to the desorption of metastable atoms via the formation of negative ions\(^6\) on and/or below the Ne surface.

### 4. Summary

We developed a UHV-compatible low-energy electron gun that uses the photoelectric effect. A single-crystal LaB$_6$(100) cathode and a laser diode ($E_{ph} = 2.62$ eV) generated a photoelectron beam with an energy width of 0.11 eV without using an energy selector; the maximum current was 38 nA. The photoelectron current decreased...
with time but was easily recovered upon cathode cleaning.

We estimated the photoelectron energy width using a simple model that closely followed our results.

The developed electron gun was used to study the electron-stimulated desorption of metastable Ne atoms from a solid Ne surface. The gun demonstrated sufficient characteristics for probing electron-induced surface phenomena.

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