JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 25, NO. 1, JANUARY, 1986, pp. 64-67

Vacuum Ultraviolet Light Source Using Electrodeless Discharge

Chun-Lin SHAO, Takashi JIMBO, Masayoshi UMENO[††]
and Shuzo HATTORI[†]

Department of Electronics,
[†]Department of Electronic Mechanical Engineering,
Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464
[††]Department of Electronics and Computer Engineering,
Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466

(Received June 21, 1985; accepted for publication October 26, 1985)

A new type of vacuum ultraviolet light source employing electrodeless pulse discharge was studied, and the discharge conditions needed to obtain stable VUV radiation were investigated. The argon discharge spectra between 50 nm and 110 nm were studied, and the number of photons detected through a monochromator was estimated to be 2.5×10^{11} $cm^{-2}s^{-1}$ at a photon energy of 13.48 eV, a pressure of 5 mTorr of argon, and a flow rate of 12 cm^3/min.

§1. Introduction

The great variety of experiments carried out in the vacuum ultraviolet (VUV) radiation region necessitates a corresponding variety of VUV light sources, such as continuous spectrum sources, line sources, intense pulse radiation sources, and DC light sources. Various VUV light sources have been developed.[1,2] One of these is the duoplasmatron, usually used as a DC VUV source, which can produce many lines of good intensity between 40 nm and 100 nm at low pressures around several hundred mTorr.[3] Other hot-filament arc-discharge and cold-cathode discharge devices are also used, and synchrotron radiation as a continuum source can cover the VUV wavelength range.[4]

The conventional photolithography used in the production of integrated circuits is carried out in the 450 nm to 310 nm spectral region, which gives a spatial resolution of about 1 to 1.5 μm. However, for very large scale integration (VLSI) production, higher spatial resolution is necessary. The spatial resolution can be increased by reducing the wavelength of the exposure radiation to the deep UV or the VUV.[5] Accordingly a light source with VUV wavelength is needed. Furthermore, to improve the quality of VLSI devices, dry processes such as VUV light-induced chemical etching or deposition are required.[6] Therefore a low-cost light source which can produce strong VUV radiation is desirable. The aim of this study was to develop a VUV light source to be used as an exposure light source for VUV photolithography, and for possible use in light-induced chemical etching or deposition.

This paper describes the fundamental characteristics of a VUV light source obtained by improving an electrodeless ring discharge tube developed for use in a pulsed argon ion laser.[7] The electrodeless discharge has the following advantages: (a) There are no problems due to damage to metal electrodes, and no influence of radiation emitted from metal impurities sputtered from electrodes on the discharge gas spectrum. (b) Since a large amount of electric power can be injected to excited the discharge gas, a strong radiation pulse can be obtained.

This paper reports a vacuum ultraviolet light source using electrodeless discharge, and describes the discharge conditions required to obtain strong VUV radiation. The argon discharge spectrum in the VUV region was measured and the numbers of emitted photons were estimated.

§2. Construction of the Light Source

Figure 1 is a schematic diagram of the vacuum ultraviolet light source. The apparatus consists of five parts; a ring discharge tube, an RF generator for preionization of the gas, a pulse power supply, a gas feed system with gas flow meter F, and a gas pumping system.

The ring discharge tube consisted of a quartz pipe with a wall thickness of 2 mm and a total length of 1240 mm. To increase the plasma density at the light source section, a pipe with an internal diameter of 6 mm was chosen for this section. The other part of the ring tube has an internal diameter of 26 mm. The ratio of the cross-sectional area of the large tube to that of the source section is about 19, and thus the current density in the light source section can be up to 19 times that in the other part.

The ring tube can be evacuated to a base pressure of 1×10^{-6} Torr by the gas pumping system. Argon is used as the working gas for easy initiation of discharge because of its low ionization potential. The flow rate can be controlled and measured with the gas flow meter, and the pressure in the ring tube can be adjusted to a fixed value in the range $2\sim40$ mTorr at a flow rate of 12 cm^3/min by controlling the pumping power.

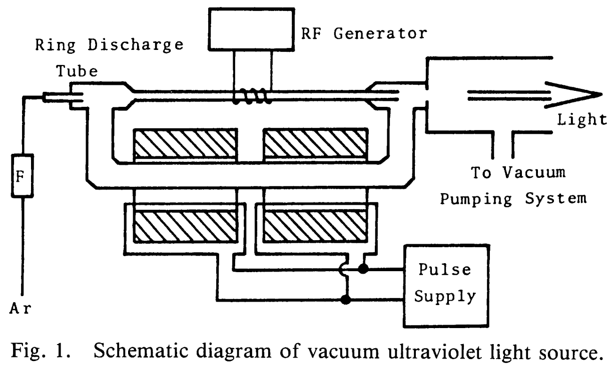
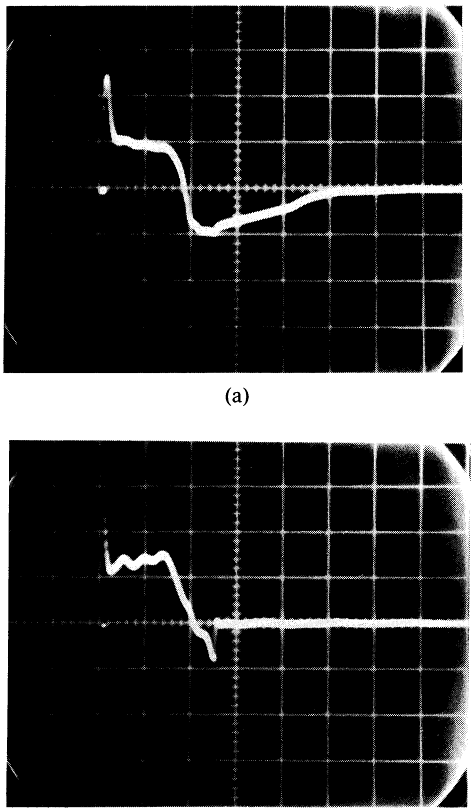


Fig. 1. Schematic diagram of vacuum ultraviolet light source.

The ring discharge tube itself operates as a secondary circuit of the transformer, which has two magnetic cores of length 200 mm and cross section 100 cm^2. Each core is would with a one-turn primary coil. A pulsed voltage with a maximum of 250 V is applied to the two primary coils, which are connected in parallel.

The frequency of the RF generator used for preionization of the argon is 35 MHz, and its average power is 50 W. The RF power is supplied to the discharge tube after the latter has been filled with a discharge gas at a certain pressure. The powerful pulse supply can generate pulses with a duration of 36 μs at a repetition rate of 80 pulses per second. Once a pulse voltage with the waveform shown in Fig. 2(a) is applied across the primary of the transformer, the pulse current shown in Fig. 2(b) flows through the primary. The induced voltage applied to the ring discharge tube as an excitation source enhances the ionization state of the discharge gas, kept in the weakly-ionized state by the RF generator. The peak discharge current through the ring discharge tube was measured as 125 A using a Rogowski coil at a flow rate of 12 cm^3/min and a pressure of 5 mTorr.



(a)

(b)

Fig. 2. (a) Waveform of pulse voltage applied to primary of transformer. The scale of the horizontal axis is 20 μs/div and that of the vertical axis is 100 V/div.
(b) Waveform of current in primary. The scale of the horizontal axis is 20 μs/div and that of the vertical axis is 400 A/div.

§3. Experiment and Discussion

3.1 *Spectrum in VUV region*

A schematic diagram of the measuring device is shown in Fig. 3. No window was used between the light source and the monochromator, since no suitable material exists which transmits radiation below 105 nm, the short-wavelength transmisson limit of lithium fluoride. Therefore a differential pumping system was needed between the light source and the monochromator. The radiation from the VUV light source passes through the differential pumping chamber into the entrance slit of the monochromator (VM-502, Acton Research Co.), which has a focal length of 20 cm, an aperture ratio of f/4.5 and a reciprocal dispersion of 4 nm/mm.

The vacuum ultraviolet detector used is a Cu–BeO dynode electron multiplier tube (R 595, Hamamatsu Photonics Co., Ltd.) with 20 dynode stages. Its sensitivity remains constant during the experiments and is little affected by exposure to air. The electron multiplier tube was calibrated beforehand by Hamamatsu Photonics co., Ltd. Its quantum efficiency is greater than 1.5 percent in the region from 150 nm down to 30 nm, and has a maximum of about 15 percent at 70 nm.

Thanks to the low operating pressure in the discharge tube and the small slit area of the monochromator, the pressure in the detector could be kept at 2×10^{-5} Torr by evacuating the monochromator and the vessel with a turbomolecular pump. The voltage applied to the electron multiplier tube was 1.6 kV. The output of the electron multiplier tube was fed to a digital boxcar integrator (BX-531, NF Electronic Instruments), and a pen recorder was employed to record its integrated and amplified output signal.

Figure 4 shows the argon spectra between 50 nm and 110 nm under an argon pressure of 5 mTorr, an argon flow rate of 12 cm^3/min and the input voltage shown in Fig. 2(a). With the exception of some impurity lines from OII, NII and NIII, the spectra come primarily from ArII and ArIII lines.

3.2 *Intensity*

The light intensity incident on a sample is of interest from the point of view of light-induced etching or

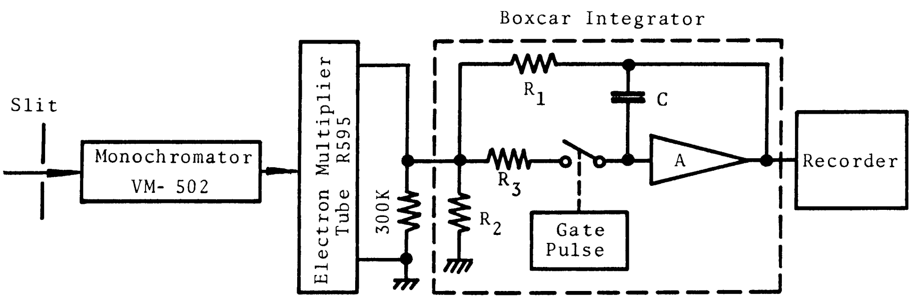


Fig. 3. Schematic diagram for spectral measurements.

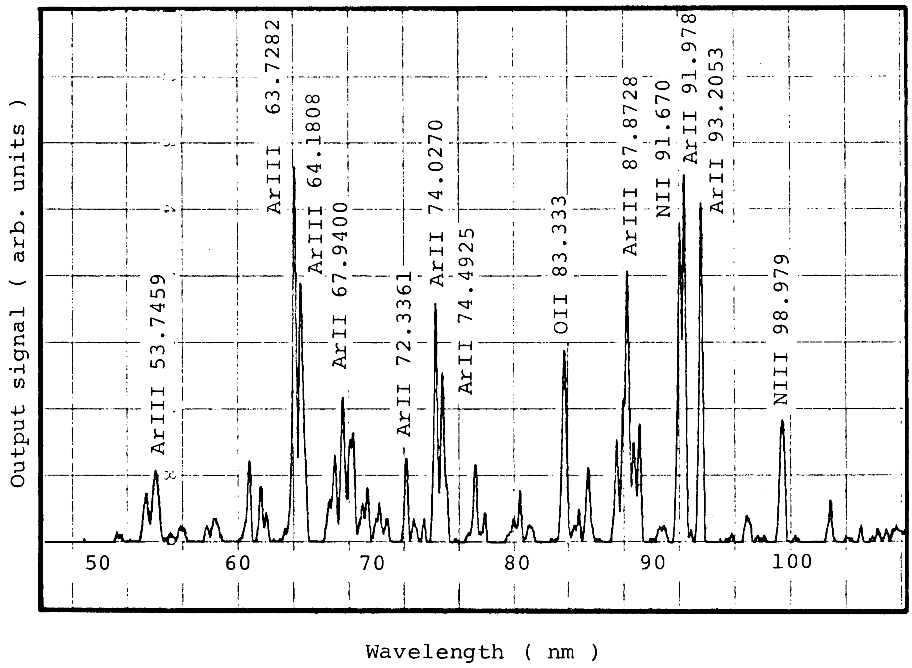


Fig. 4. Typical argon spectra between 50 nm and 110 nm produced by vacuum ultraviolet light source obtained at a pressure of 5 mTorr and a flow rate of 12 cm^3/min.

photolithography. In order to estimate the intensity, we need to know the brightness on the exit slit of the monochromator. The entrance slit and the exit slit of the monochromator were set to 0.1 mm × 10 mm, and an electronic circuit similar to that shown in Fig. 3 was used. However, the boxcar integrator was replaced by an oscilloscope for direct observation of the light waveform.

The number of photons detected through the monochromator was estimated from the value of the photocurrent, obtained from the voltage drop across a standard resistor, the current amplification, and the quantum efficiency of the electron multiplier tube. The quantum efficiency at 91.978 nm had been measured as 13 percent, so this line was used in our experiment. The peak value of the photon flux density at the exit slit of the monochromator was found to be 2.5×10^{11} photons $cm^{-2}s^{-1}$ at a photon energy of 13.48 eV (corresponding to a wavelength of 91.978 nm) at a flow rate of 12 cm^3/min and a pressure of 5 mTorr. This photon flux density is about 5 percent overestimated, because this line is overlapped by an N II line as shown in Fig. 4. The lower energy level relevant to this line is an excited level of Ar^+ ($3p^5\ ^2P^0$—$3p^6\ ^2S$) and therefore its population density is considered to be so small that the absorption effect can be neglected. The intensity can also be obtained for other lines by a similar method or by estimating it from the relative intensity and the quantum efficiency of the electron multiplier tube.

Generally speaking, VUV lines are strongly absorbed by air. At one atmosphere and zero degrees centigrade, the absorption coefficient of oxygen for VUV radiation is smaller than 1000 cm^{-1}, and the nitrogen is transparent in the region from 100 nm to 200 nm.[8] In the experiment, the pressure in he light transmission chamber is about 2×10^{-5} Torr, and assuming the absorption coefficient of air to be 1000 cm^{-1} at a wavelength of 91.978 nm, the attenuation of the 91.978 nm line by absorption by air is less than 0.3 percent even if the light path length amounts to 1 meter. Therefore, the attenuation of VUV lines can be neglected in the experiment.

3.3 *Stability*

The dependence of the light intensity on the experimental conditions was investigated, and it was found that when the pulse voltage applied to the primary of the transformer was increased by 5 percent, the light intensity increased by 24 percent. A variation of the gas pressure of up to 5 percent resulted in a change of at most 1.2 percent in the light intensity, but the light intensity did not depend heavily on the flow rate. The main factor dominating the stability of the light intensity was found to be the stability of the input voltage. It is easy to obtain a high-stability voltage source, and therefore a stable light source will be practicable. In the present experiment, the variation in the output light intensity could be kept within 0.5 percent.

§4. Conclusions

An electrodeless discharge-type VUV light source has been developed, and the argon discharge spectra in the VUV region have been observed. The peak value for the photons detected at the exit slit of the monochromator was found to be 2.5×10^{11} photons $cm^{-2}s^{-1}$ at a photon energy of 13.48 eV, a pressure of 5 mTorr and a flow rate of 12 cm^3/min. The Variation of the output light intensity was about 0.5 percent. The light source can be used both as a spectroscopic light source and as an exposure light source for VLSI lithography. It can also be employed in photochemistry studies. If the light intensity is strengthened further by increasing the average power of the input pulse, the source will be suitable as a VUV light source for light-induced chemical etching or deposition.

Acknowledgements

The authors wish to express their thanks to Associate Prof. Toshio Goto and Dr. Yoshiyuki Uchida of Nagoya University for helpful discussions and advice, and to Mr. Kazuhiro Tomita of the Nagoya Institute of Technology for his help with the measurements. They are also grateful to Prof. Masamoto Otsuka and Mr. Kazushige Ishii of the Institute of Plasma Physics of Nagoya University for many helpful discussions and assistance. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture.

References

1) J. A. R. Samson: *Techniques of Vacuum Ultraviolet Spectroscopy* (Wiley and Dons, New York, 1967) p. 94.
2) T. Namioka and T. Sagawa: J. Spectrosc. Soc. Jpn. **22** (1973) 265.
3) J. A. R. Samson and H. Liebl: Rev. Sci. Instrum. **33** (1962) 1340.
4) S. Krinsky, M. L. Perlman and R. E. Watson: *Handbook on Synchrotron Radiation*, ed. by E. E. Koch (North-Holland, New York, 1983) Vol. 1A, p. 65.
5) B. J. Lin, E. Bassous, V. Chao and K. Petrillo: J. Vac. Sci. Technol. **19** (1981) 1313.
6) C. Shao, T. Jimbo, M. Umeno and S. Hattori: The Review of Laser Engineering **13** (1985) 14. [in Japanese]
7) S. Hattori and T. Goto: J. Appl. Phys. **39** (1968) 5998.
8) R. Onaka: Jpn. J. Spectrosc. Soc. **19** (1970) 350 [in Japanese].