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Emission of Short-Wavelength Photons from Ion-Surface Charge Exchange

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Abstract—The intensity of radiation emitted from ion-surface charge exchange processes can be significantly enhanced if the surface exposed to impinging ions is electronically excited. Alpha particles capturing electrons at a silicon surface are considered as possible candidates for a short-wavelength laser.

I. INTRODUCTION

It has been proposed [1] that some selected charge exchange processes may serve as a means of achieving population inversion for short-wavelength lasers [2]. Recent observation [3] of strong VUV and X-ray emission from laser-produced

Manuscript received January 21, 1983; revised July 18, 1983. The work of H.-W. Lee was supported in part by the Petroleum Research Fund, administered by the American Chemical Society, a Grant from the Research Corporation and by an Oakland University Research Fellowship. The work of T. F. George was supported in part by the National Science Foundation under Grant CHE-8022874, the Air Force Office of Scientific Research (AFSC), United States Air Force, under Grant AFOSR-82-0046, the Office of Naval Research, and the U.S. Army Research Office.

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plasmas suggests a possibility of utilizing charge exchange in compound solids. For example, one might irradiate a compound solid with a high-power laser beam in order to preferentially excite one of the atomic species in the solid. The population inversion in the other atomic species could then be obtained through charge exchange that ensues between the two species.

Two independent investigations have focused on the possibility of using ion-surface charge exchange processes to obtain coherent short-wavelength radiation [4], [5] where the former [4] further suggested laser excitation of the surface. It is known that collisions of positive ions with a metal or semiconductor surface, e.g.,

can produce excited atoms or ions and subsequent photon emission [6]. Under normal conditions, the intensity of emitted radiation is generally too low to even suggest the possibility for a laser. However, it has been suggested [4] that the intensity can be significantly enhanced if the surface exposed to impinging ions is electronically excited. Such excitation of a surface can be achieved by infrared or visible radiation

which can effectively promote electrons to surface bands. As an illustration, we consider a collision of an alpha particle with an electronically excited silicon surface which produces excited singly ionized helium. Rough estimates of the charge exchange cross section and the laser gain are presented.

II. THEORY

When a positive ion A^{m+} collides with a metal or semiconductor surface S , it can capture an electron at the surface.

The probability P for this charge exchange to occur is given by [4]

$$P = 1 - \exp \left[-2 \int_{-\infty}^{\infty} dt \Gamma(t) \right] \quad (1)$$

where the instantaneous transition rate $\Gamma(t)$ can be written as

$$\Gamma(t) = N_{E_0}^2 \Gamma'(t). \quad (2)$$

$\Gamma'(t)$ is a complicated function which depends on various parameters of the ion and the solid, and N_{E_0} is a normalization constant for an electron of energy E_0 in the solid where E_0 represents the resonance energy, i.e., the transfer of an electron of energy E_0 in the solid to the ion is an energy conserving process. The charge exchange cross section σ can be estimated as

$$\sigma \simeq \pi z_0^2 P \quad (3)$$

where z_0 is the ion-surface separation at which the electron capture occurs. We note that the normalization constant N_{E_0} and consequently the charge exchange probability and cross section are generally much greater for a surface electron than for a bulk electron. This simply means that surface electrons are much easier to be picked up by the incoming ion than bulk electrons. The number density of the product $A^{(m-1)+}$ is therefore enhanced if bulk electrons are excited to surface bands. Such excitation of a surface can be achieved by irradiating the surface with a source of appropriate power and wavelength.

Regarding a possible short-wavelength laser, we of course are interested in the process in which the product $A^{(m-1)+}$ is produced predominantly in an excited state capable of emitting a short-wavelength photon. The gain of a Doppler-broadened medium is then given by the expression [7]

$$g \simeq \sqrt{\pi \ln 2} \frac{\lambda^2}{8\pi} \frac{\Delta N}{\tau_s \Delta \nu} \quad (4)$$

where $\Delta \nu$ and λ are, respectively, the linewidth and wavelength of the transition in question, τ_s is the spontaneous lifetime of the upper level, and ΔN is the inversion density. In our case, ΔN is given by

$$\Delta N \simeq N_{\text{ion}} N_e v \sigma \tau_s \quad (5)$$

where N_{ion} and N_e are the number densities of the incident ions and surface electrons, respectively (the effect of bulk electrons is neglected), and v is the velocity of the incident ions. It is clear that in order to obtain the high gain required for laser action in the short-wavelength region, one needs a high inversion density ΔN , which in turn puts the burden on the power of the excitation beam that must supply a sufficient number of surface electrons.

Fig. 1. Energy levels of $\text{He}^{2+} + \text{Si}(111)$. The valence and conduction bands are labeled by V and C , respectively, with an energy gap of 1.11 eV.

III. EXAMPLE—ALPHA PARTICLE AT A SILICON SURFACE

Let us consider an electron capture process of an alpha particle at a silicon(111) surface

A look at energy level structures of He^+ and a silicon surface (see Fig. 1) suggests that the helium ion is produced predominantly in its second excited state, $\text{He}^+(3l)$. Subsequent Balmer α and Lyman β transitions produce radiation at $\lambda = 164$ nm and $\lambda = 25.6$ nm, respectively.

The charge exchange probability P as given by (1) can be written as

$$P \approx 1 - \exp \left[-\frac{4}{v} \int_0^\infty dz \Gamma(z) \right] \quad (6)$$

where z is the ion-surface separation, and a straight line trajectory with velocity v is assumed for the ion. The evaluation of the above requires a detailed knowledge of the potential energy surfaces and surface states involved. Since the electron capture occurs at relatively large ion-surface separations, the potential energy surfaces are assumed to be determined mainly by image forces. For silicon, we adopt the one-dimensional model of a semiconductor [4] and take W (work function) = 4.6 eV, E_g (gap energy) = 1.11 eV, ρ (density of surface states)/area = 4×10^{14} /eV $\cdot$ cm 2 , and K (dielectric constant) = 11.8. The integral can then be carried out numerically, and we obtain $P \simeq 0.097$ for the case $v = 0.1$ a.u. = 2.2×10^7 cm/s. The resonance transfer of surface electrons occurs at $z_0 \simeq 7$ – $12 a_0$ (a_0 : Bohr radius), which yields $\sigma \simeq 49\pi \times 0.097 \simeq 15.0 a_0^2 \simeq 4.19 \text{ \AA}^2$ at $v = 2.2 \times 10^7$ cm/s. This cross section appears to be sufficiently large to warrant our consideration of

a short-wavelength laser utilizing the He^{2+} -Si(111) system. However, one must supply a sufficiently high density of ions and, in particular, surface electrons in order to obtain the high gain. This problem is considered below.

For a short-wavelength laser, the gain g is desired to be $\sim 10/\text{cm}$ or higher, requiring a high inversion density ΔN [see (4)]. For the Balmer α transition we have $\lambda = 1.64 \times 10^{-5} \text{ cm}$ and $\tau_s = 1.4 \times 10^{-9} \text{ s}$. Taking $g = 10/\text{cm}$ and the Doppler width $\Delta\nu \cong 10^{10} \text{ Hz}$, we obtain $\Delta N \cong 8.9 \times 10^{12}/\text{cm}^3$. With $v = 2.2 \times 10^7 \text{ cm/s}$ and $\sigma = 4.19 \text{ \AA}^2$ as calculated above and taking $N_{\text{ion}} \cong 10^{13}/\text{cm}^3$, we then obtain, from (5), $N_e \cong 6.9 \times 10^{16}/\text{cm}^3$. This corresponds to the surface electron density of $n_e \cong 7.6 \times 10^9/\text{cm}^2$. The requirement on the power of the excitation source in order to populate this many surface electrons does not seem to be severe at all. We mention that a rough estimate shows that, with a power density of 1 W/cm^2 tuned at $\hbar\omega = 2E_g/5$ (ω = laser frequency), the number of electrons excited to surface bands is on the order of $10^{10}/\text{cm}^2/\text{s}$.

For the Lyman β transition, we have $\lambda = 2.56 \times 10^{-6} \text{ cm}$ and $\tau_s = 1.1 \times 10^{-9} \text{ s}$. Taking again $g = 10/\text{cm}$ and $\Delta\nu \cong 10^{10} \text{ Hz}$, we obtain, from (4), $\Delta N \cong 2.9 \times 10^{14}/\text{cm}^3$. Thus, the gain of $10/\text{cm}$ cannot be obtained unless $N_{\text{ion}} \gtrsim 2.9 \times 10^{14}/\text{cm}^3$. If we take $N_{\text{ion}} = 10^{14}/\text{cm}^3$ and accordingly $\Delta N = 10^{14}/\text{cm}^3$, we obtain, using (4), the maximum possible gain of $g \cong 3.5/\text{cm}$. In order to achieve $\Delta N \cong 10^{14}/\text{cm}^3$, one must have $N_e = 9.9 \times 10^{16}/\text{cm}^3$ [see (5)] which corresponds to the surface density $n_e \cong 1.1 \times 10^{10}/\text{cm}^2$. The requirement on the power of the source to excite this many electrons is again not severe.

It should be noted that in our treatment we have neglected Auger processes which may contribute to the decrease of gain. Through Auger processes, incident alpha particles can produce helium ions in their ground state accompanied by ejection of electrons [8], [9]. Furthermore, excited helium ions produced by charge exchange may be quenched by Auger deexcitation before they escape the surface [8], [9]. Although there are some indications [8] that the probability for Auger deexcitation is small for the velocity range ($\sim 10^7 \text{ cm/s}$) considered here, it seems desirable that the relative importance of resonance charge exchange compared to Auger processes (especially for surface electrons) be further investigated. We also mention that our analysis is based on the one-dimensional model [4] of a surface according to which a semiconductor has a direct gap. In reality, however, semiconductors like silicon have an indirect gap, and the excitation of electrons into surface bands by radiation may have to be accompanied by phonon excitations [10].

ACKNOWLEDGMENT

T. F. George acknowledges the Camille and Henry Dreyfus Foundation for a Teacher-Scholar Award (1975-1984) and the John Simon Guggenheim Memorial Foundation for a Fellowship (1983-1984).

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Table-Top EUV Continuum Light Source

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Abstract—Work in recent years on the development of a convenient "table-top" source of continuum radiation in the XUV and VUV from 4 to 200 nm is summarized. It was found that laser-produced plasmas on targets of high atomic number ($62 \leq Z \leq 74$) emitted apparently line-free continua over very substantial spectral regions in the XUV and VUV. The continua are very intense, reproducible, and relatively insensitive to ambient pressure. The effective absence of line emission can be explained on the basis of the electron configurations of the ionized species responsible for the emission. A high repetition rate modular version of the source is described. Applications and advantages of the light source are presented.

I. INTRODUCTION

THE development of the synchrotron as a source of continuum radiation has led, in recent years, to a considerable growth of activity in such areas as absorption spectroscopy and photoionization in the VUV and the XUV regions. Although very effective as a light source, the synchrotron has the extreme disadvantages of being very costly and nonportable, and the need for a much simpler and cheaper light source is very apparent. We believe that the simple compact light

source described in the present paper and which was developed initially in the Department of Physics, University College, Dublin, Ireland, has much to offer and indeed has been used successfully on a routine basis as a table-top source in our laboratory [1], [2].

II. EARLY EXPERIMENTS WITH LASER-PRODUCED CONTINUA

Shortly after the development of the giant pulse *Q*-switch laser it was found that when its output was focused on a solid target material in vacuum, a dense high-temperature plasma was generated. The spectra of such plasmas were found typically to originate in species in high stages of ionization. Many new spectra were generated and studied in this way; as typical examples, we quote the work of Fawcett [3] and Doschek *et al.* [4]. In all these cases the spectra were dominated by strong line emission and the thrust of the work was on conventional term analysis. To a greater or lesser extent continuum originating in recombination and bremsstrahlung was always present. Because of the dominance of strong lines, however, the continuum was quite unsuitable as a background for absorption studies.

A systematic study of target materials was undertaken in this laboratory with the hope of finding a spectrum in which the lines would be, to a greater or lesser degree, suppressed with respect to the continuum. In the course of this work almost all the heavier elements from strontium ($Z = 38$) to uranium

Manuscript received February 7, 1983; revised September 2, 1983. This work was supported in part by the National Board for Science and Technology (Ireland) under Research Grant URG/143/82 and by the NSF under Grant PHT 80-16657.

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