

Smith–Purcell radiation using a single-tip field emitter

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We have successfully observed Smith–Purcell radiation (SPR) using a single-tip *n*-type Si field emitter in the visible wavelength from 400 to 700 nm at low input power level with beam currents of 20–200 nA and accelerating voltages of 25–30 kV. Several peaks corresponding to the third and fourth harmonics of SPR are obtained using a 550 nm period metal grating and redshifted with decrease of the acceleration voltage. The measured peaks are well explained by the SPR theory. © 2005 American Vacuum Society. [DOI: 10.1116/1.1851536]

I. INTRODUCTION

Smith–Purcell radiation (SPR) is generated by the interaction between electron beam and electric field on a diffraction grating surface, as shown in Fig. 1, and covers a broad band ranging from visible light to millimeter waves.^{1–3} The radiated wavelength of SPR is expressed by

$$\lambda = d(1 - \beta \cos \theta)/n\beta,$$

where λ is wavelength, d is the grating period, θ is the emission angle (0° refers to the parallel to electron beam), n is the diffraction order, and β is the ratio of electron velocity to light one. Potential applicability of field emitter arrays (FEAs) to a free electron laser using SPR has been pointed out by several authors because of FEA's capability of yielding low-emittance high brightness electron beam and for miniaturization of the SPR apparatus.^{4–7} The detection of the SPR using FEAs was reported at relatively large input power level with beam currents of 5–25 μA and accelerating voltages of 40–100 kV.^{5,6}

In this paper we describe SPR in the visible wavelength by using a single-tip *n*-type Si field emitter at low input power level with beam currents of 20–200 nA and accelerating voltages of 25–30 kV. We aim to develop an efficient and miniature-size free electron laser, which is the reason why we did the SPR experiment at very low input power level. But SPR intensity has strong dependence on beam current, Strong radiation could not be expect using low input power. Moreover, the reason of using a semiconductor field emitter is that the emission current from a semiconductor field emitter is relatively easily modulated by laser irradiation,⁸ leading to the formation of bunched beam (pulsed beam train) for the enhancement of SPR due to co-

herent effects.² Although we detect the SPR in the visible wavelength because of easy availability of the corresponding detector, we are going to detect the SPR in the THz region as the next step.

II. EXPERIMENTS

Single-tip Si field emitters with a conical shape were fabricated by a conventional method using reactive ion etching (RIE) and thermal oxidation sharpening.^{9,10} An *n*-type (100)-oriented single-crystal Si wafer with a resistivity of 2–3 Ωcm was used as an emitter substrate. The emitter has a 1.5 μm diameter gate aperture and a 1 μm tip height. Typical current–voltage (*I–V*) characteristics of the single-tip *n*-type Si field emitter is shown in Fig. 2. The gate current is negligibly small, as compared with the emission current.

Figure 3 shows the SPR experimental apparatus. All SPR experiments were carried out in an ultra high vacuum chamber, which was pumped below 1.5×10^{-7} Pa. The field emitter was set on a cathode shank, located in the center of the chamber and biased at about –30 kV. The cathode shank has

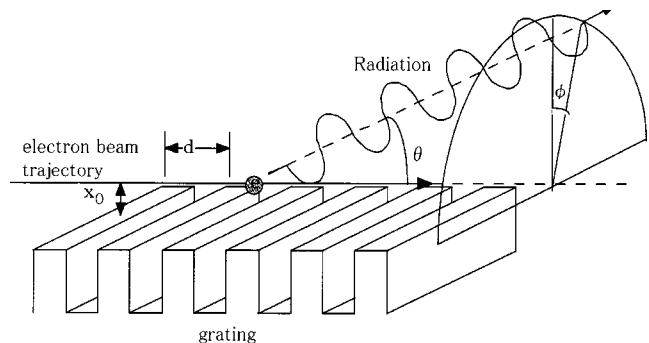


FIG. 1. Schematic layout of SPR.

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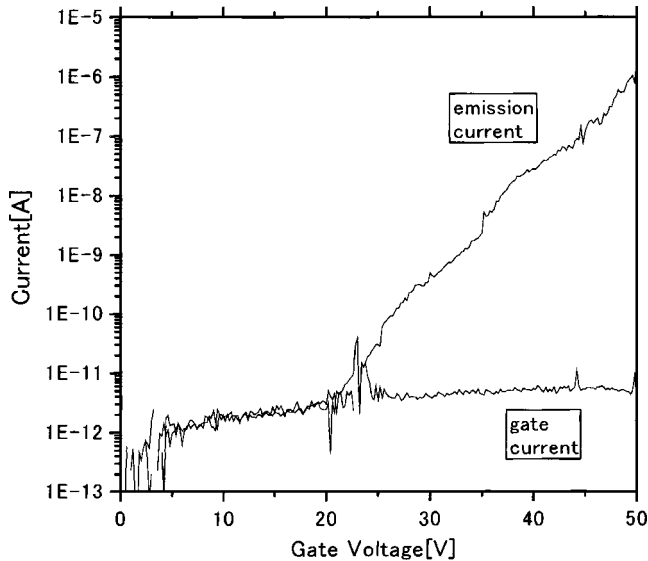


FIG. 2. Typical I - V characteristics of a single-tip n -type Si filled emitter.

a wehnelt geometry which was designed for electron beam sharpening using a simulator. For strong SPR, electron beam must skim the grating, because the electric field interacting with the electron beam decreases exponentially with increasing the beam height (X_0 in Fig. 1) from the grating surface. An aluminum-coated replica grating with 2.5 cm wide and 2.5 cm long was located at 3 cm in front of the cathode so that electron beam from the cathode passed over the grating surface (see Fig. 3). The anode consisting of two parts, upper and lower plates separated by a 0.5 mm wide aperture, was set on the entrance side of the grating. Both plates also work as a deflector by applying a bias voltage of ± 500 V on each plate. A grating with a period of 550 nm was used in the experiments. This corresponds to SPR wavelength, calculated by the SPR theory, of 600 nm at an acceleration voltage

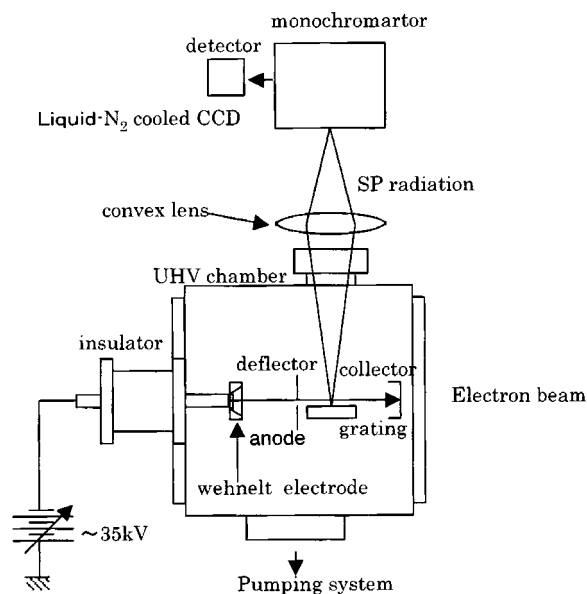


FIG. 3. Schematic set-up of SPR experiments.

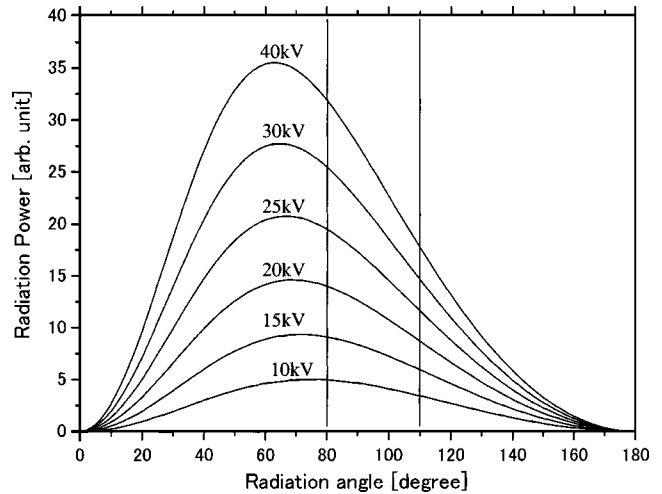


FIG. 4. Theoretical dependence of SPR intensity on the radiation angle.

of 27.5 kV, an emission angle of 90° and a diffraction order of 3. SPR were detected through a viewing port. We collected SPR with an emitting angle between 80° to 110° using a convex lens. However, it should be noted that as shown in Fig. 4, the peak intensities are not located in the emitting angle range going from 80° to 110° . A liquid- N_2 cooled CCD detector was used for the detection.

III. RESULTS AND DISCUSSION

Figure 5 shows the SPR spectra measured by using a 550 nm period grating. SPR is clearly observed in the following conditions: The gate voltage of the Si emitter is 80 V, which corresponded to an emission current of a few μA . We did not measure the emittance of the electron beam. The diameter of the electron beam was 2–3 mm even using the wehnelt electrode. Therefore, the deflectors cut almost 90% of the emission current, and the real traveling current on the

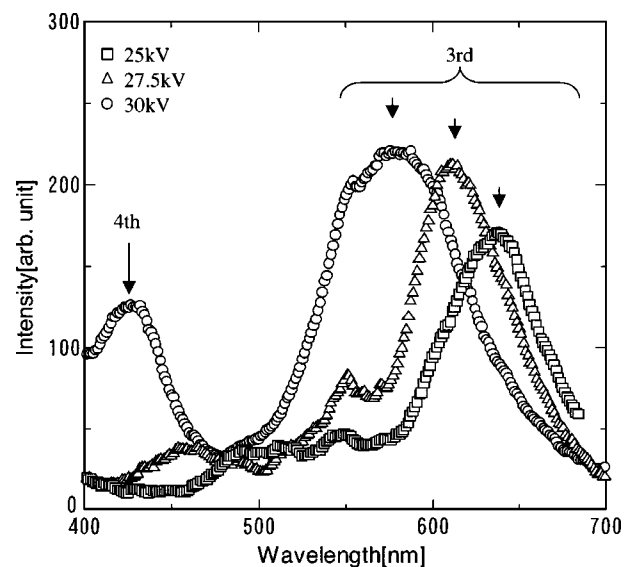


FIG. 5. SPR spectra for the acceleration voltages of 25 kV, 27.5 kV, and 30 kV.

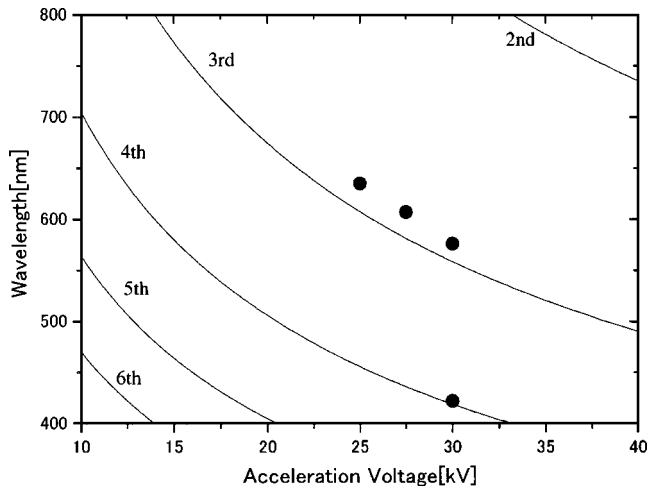


FIG. 6. Dependence of the SPR wavelength on the acceleration voltage. Solid lines and circles are the calculated and measured results, respectively.

grating was about 20–200 nA. The collector current was almost equal to the real traveling current. The acceleration voltages are -25 kV, -27.5 kV, and -30 kV. Several peaks, corresponding to the third and fourth harmonics of SPR, are obtained and redshifted with decrease of the acceleration voltage. The SP intensity is proportional to the collector current. The SPR peaks are rather broad, for example, full width at half maximum (FWHM) of the third harmonic of SPR at 30 kV is 100 nm.

Figure 6 shows the dependence of the SPR wavelength on the acceleration voltage for the emitting angle of 90° . Solid lines and circles are the calculated and measured results, respectively. The measured peaks almost coincide with the calculated ones, though there is a small discrepancy between them. The reason of this discrepancy is that the center of the detection angle in the experiment is not just 90° . The dependence of the SPR wavelength on the radiation angle at the acceleration voltage of 30 kV is shown in Fig. 7. When the center of the detection angle is larger than 90° , the measured peaks deviate from the solid lines to the longer wavelength side. Moreover, we collected SPR with emitting angles from about 80° to 110° using a convex lens in this experiment. It is reasonable to explain that the broad spectra is due to the large detection angle, as shown in Fig. 7.

IV. CONCLUSION

We have fabricated a single-tip *n*-type Si field emitter with a conical shape and have started an experiment on visible SPR to practical applicability of a field emitter to a compact free electron laser. We used an aluminum-coated 2.5 cm wide and 2.5 cm long replica grating with a period of 550 nm and successfully observed SPR at wavelengths going from 400 to 700 nm at low input power level such as beam currents were between 20–200 nA and accelerating voltages were between 25–30 kV. Several peaks corresponding to the third and fourth harmonics of SPR are obtained and red-

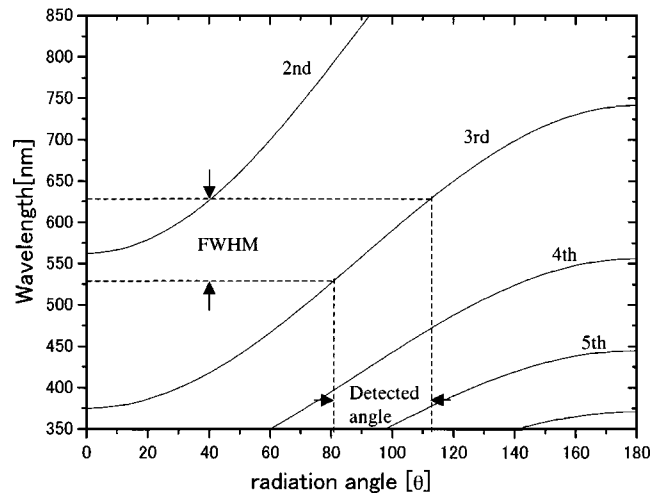


FIG. 7. Dependence of the SPR wavelength on the radiation angle at the acceleration voltage of 30 kV. Dashed lines point out the relation between the expected FWHM and detected angle.

shifted with decrease of the acceleration voltage. The measured peaks and their broadening are well explained by the SPR theory. These results indicate that a semiconductor field emitter is a promising electron source for compact free electron lasers.

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