High-Brightness Bunched Electrons Using a Semiconductor Photocathode and Optimized Acceleration Field

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Photocathode-type electron source for electron microscope, which is laser controllable emitter using photoelectron, is expected to achieve high spatial and high temporal resolutions simultaneously. Spin-polarized Pulsed-TEM (SPTEM) have been successfully developed using a semiconductor photocathode with a negative electron affinity (NEA) surface as a photocathode-type electron source [1-2]. Several beam parameters of the electron gun are superior to those of conventional thermal electron beams. In addition, that has an ability to generate a picosecond pulse-beam [3].

In continuous beam emissions, we have demonstrated that the SPTEM can provide both TEM images and diffraction patterns [2]. The TEM images were obtained at a spatial resolution of 1 nm with a 30-kV acceleration voltage. The brightness was measured by taking a spot size and a convergent angle on an image plane. The measured brightness is approximately $4 \times 10^7$ A cm$^{-2}$ sr$^{-1}$ at 30-keV beam energy with a drive-laser power of 800 kW/cm$^2$ on the photocathode.

Pulse beam emission in the SPTEM was also performed using a combination of the semiconductor photocathode and an ultra-short pulse laser, which can realize a time-resolved measurement with stroboscopic technique or single-shot technique. The photocathode has high quantum efficiency on the order of $10^{-3}$ compared with other metal-type photocathodes, which can realize not only a continuous emission but also a picosecond pulse emission. Time-resolved TEM imaging and pulsed interference fringes were also successfully conducted using a stroboscopic acquisition method [4, 5].

However, the apparatus still needs to be improved for higher temporal resolution. It is a low brightness of the pulsed electron beam due to space charge effect in a high-charge operation. This leads long exposure time required for the stroboscopic technique and the pulse duration restricted about 100 ns for the single-shot technique. Therefore, we assumed acceleration voltage was required to be higher than 30 kV for suppressing the space charge effect in the acceleration field.

We performed beam simulation of the picosecond pulsed electron beam emitted from the semiconductor photocathode including the electron geometric information, which was taking account of the space charge effect. The simulation was conducted with 1-ps driven laser and 1-μm emission spot. The initial temporal structure of the pulse laser and spot size were set as Gaussian distribution. The initial velocity of electron was 0.1 eV due to an NEA surface potential of the photocathode. Figure 1 shows the simulation results of the brightness of pulsed electron beam and that pulse duration as a function of charge density per pulse. As the acceleration voltage is increasing, the brightness and the pulse duration become higher and shorter at same charge density per pulse, respectively. Altogether, higher acceleration voltage restrains the space charge effect due to the high acceleration field. The brightness of 300 kV is one order of magnitude higher than that of 50 kV. Furthermore, the degradation of pulse duration is suppressed at the acceleration voltage of 300 kV, which is half as that of 50 kV.

In the case of same acceleration voltage, we find that degradation of brightness including the beam emittance is difference for each charge density. At small charge region in figure 1, it shows a liner increment of brightness because of negligible small of space charge effect. In contrast, at higher charge region, the brightness is increasing non-linearly. Finally, the brightness is getting decrease from 1 fC /
pulse. Figure 2 shows several charge series of distributions of macro-particles in a transverse space at 300 kV, which is evaluated at 300 ps after traveling from the cathode surface. The distribution size is small at 10 aC. However, if it becomes larger than 100 aC, the transverse beam size is increasing due to space charge effect prominently.

In summary, to suppress the space charge effect and increase the brightness, it is necessary to increase the acceleration voltage to realize a high acceleration field at the electron source. Furthermore, we should select an appropriate charge density for each acceleration voltage[6].

References
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Figure 1. Charge dependence of (a) the brightness and (b) the pulse duration driven by 1-ps pulse laser at 50 kV, 80 kV, 100 kV, 120 kV, 200 kV and 300 kV.

Figure 2. Distribution map of macro-particle for each charge density at 300 kV. The simulated charge densities are (a)10 aC , (b)100 aC, (c)1 fC, (d)5 fC.