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A High Polarization and High Quantum Efficiency Photocathode Using a GaAs–AlGaAs Superlattice*

Y. Kurihara, T. Omori, Y. Takeuchi, and M. Yoshioka
National Laboratory for High Energy Physics (KEK)
Tsukuba, Ibaraki 305, Japan

T. Nakanishi, S. Okumi, M. Tawada, K. Togawa, and M. Tsubata
Nagoya University
Nagoya, Achi 406, Japan

T. Baba, M. Mizuta
Fundamental Research Laboratories, NEC Corp.
Tsukuba, Ibaraki 305, Japan

R. Alley, H. Aoyagi,** J. Clendenin, J. Frisch, G. Mulhollan,
P. Sáez, D. Schultz, H. Tang, and K.Witte
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309, USA

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** Present address: Nagoya University, Nagoya, Aich 406, Japan.

Abstract

A charge of 2.3×10^{11} electrons in 2.5 ns at a laser wavelength of 757 nm with a corresponding quantum efficiency (QE) of 2.0% measured at 752 nm was extracted from a -120 kV biased, 20 mm diameter, GaAs–AlGaAs superlattice photocathode. The maximum electron polarization measured with material from the same wafer, but in a different system, was 71% at 757 nm for a QE of 1.0% measured at 752 nm. The quantity and temporal distribution of the extracted charge is consistent with a space charge limitation, rather than a cathode charge limit. The performance of this type of cathode makes it a possible candidate for future linear colliders.

Introduction

In the standard model of electroweak interactions, left- and right-handed electrons are treated as fundamentally distinct species, suggesting a substantial polarization dependence in many interactions. Thus for high-energy electron colliders, the sensitivity of particle detectors may be greatly enhanced by the use of a polarized electron beam. Some of the applications suggested for polarized electron beams for both present and future colliders are precise measurements of standard model parameters, observation of CP violation, and signal/background control in the search for new particles [1] .

Linear colliders are ideal for the acceleration of longitudinally polarized electrons, since there are no inherent depolarization mechanisms. A polarized electron source utilizing a GaAs photocathode has been successfully operating on a continuous basis at the Stanford Linear Accelerator for several years [2]. While continuing to meet the Stanford Linear Collider (SLC) charge requirements, the polarization of this source has been increased to about 80% [3] by using a 100 nm strained-lattice GaAs–GaAsP cathode [4]. The SLC requires two electron bunches of equal charge separated by 60 ns. At the source, each bunch must have up to 8×10^{10} electrons in a 2 ns pulse width. Future colliders, such as the Japan Linear Collider (JLC) and the Next Linear Collider (NLC), require a string of many closely-spaced bunches—as close as 1.4 ns. Although each such bunch may require as few as 1.3×10^{10} electrons, the total charge in the ~ 100 ns macropulse may need to be on the order of 10^{12} electrons.

Recent studies with polarized electron sources at SLAC [5] have revealed a new phenomenon in the physics of photoemission from negative electron affinity (NEA) GaAs photocathodes. If the quantum efficiency (QE) of a cathode is below a critical value, the maximum charge extractable using the illumination of a nanosecond-long laser pulse with a wavelength close to the cathode's band gap is determined by the intrinsic properties of the cathode, rather than by the space charge limit of the gun. This phenomenon is called the cathode charge limit effect. Quantum efficiency is here defined as the ratio of the number of photoemitted electrons to the number of incident photons before passing through the vacuum window, evaluated at low light intensities. If the QE is sufficiently high, the cathode charge limit exceeds that allowed by the space charge limit, and hence does not act as a limiting factor for maximum extractable charge. However, if the QE is below a critical value (this critical value is dependent on both the type of cathode and the cathode bias voltage), the maximum extractable charge is determined by the charge limit. In addition, for a given cathode, as the QE decays with time, the cathode charge limit is found to decrease proportionally. Therefore, high QE is a very desirable characteristic for cathodes which are to be used for the production of high-intensity polarized electron beams.

In this paper we report the result of a high-intensity beam study using a GaAs–AlGaAs superlattice photocathode. We show that very high QE at the optimal wavelength for maximum polarization can be achieved through the combined use of an As cap layer on the cathode surface and an ultraclean vacuum chamber that is equipped with a load lock system to minimize cathode surface contamination. As a result, beam intensities as high as the space charge limit of the SLAC gun operating at 120 kV have been observed.

The GaAs–AlGaAs superlattice is a semiconductor photocathode designed to produce polarized electrons. Upon illumination at normal incidence with circularly polarized photons of sufficient energy, longitudinally polarized electrons are emitted from the surface, where the degree of polarization is defined as $(N^{\uparrow}-N^{\downarrow})/(N^{\uparrow}+N^{\downarrow})$ in which $N^{\uparrow}(N^{\downarrow})$ is the number of electrons emitted with one component of spin parallel(antiparallel) to the incident photon momentum. This structure belongs to the class of materials that yields polarization greater than the 50% limit of bulk GaAs. With the superlattice, this occurs because the degeneracy between the $P_{3/2}$ heavy-hole and light-hole states is lifted by its periodic potential. In the absence of depolarizing effects, 100% polarization is theoretically possible. The maximum polarization produced by a superlattice as measured at Nagoya University is 75% [6].

Parameters of the superlattice photocathode, including thickness of the GaAs and AlGaAs layers and the fraction of aluminum in the AlGaAs layer, have been optimized to maximize the band-energy separation between the heavy-hole and light-hole states, and to assure high mobility of electrons in the cathode [7]. The optimum values obtained are: 1.98 nm for GaAs (7 monolayers), 3.11 nm for AlGaAs (11 monolayers), and an aluminum fraction of 0.35. The total thickness of the active layer was chosen to be about 95 nm in order to reduce the probability of depolarization during the emission process. The structure of the superlattice photocathode is illustrated in Figure 1.

The photocathode was p–doped to allow a negative electron affinity (NEA) surface to be achieved upon deposition of Cs and O_2 (Cs and NF_3 at SLAC). Low dopant concentration is preferable in order to maximize the polarization [8], while a high concentration is necessary to achieve the highest possible NEA surface, i.e., the highest QE. To meet these two requirements, we used the modulation doping technique: the interior of the photocathode was Be-doped at $4.8 \times 10^{17}/\text{cm}^3$, while a 5 nm thick surface layer was Be-doped at $3.8 \times 10^{19}/\text{cm}^3$ [9]. The surface of the cathode was covered by a thick arsenic cap (about 2 μm) to protect the clean surface from exposure to the atmosphere. Uncapped GaAs is normally heat cleaned for 1 hour at $\sim$ 620°C (the maximum congruent evaporation temperature) just prior to activating with Cs and an oxide. In this process, several nanometer of surface material are lost. The high doping concentration also presumably more readily diffuses at the higher temperatures. Thus a relatively low-temperature heat cleaning is necessary to retain the highly doped layer. The As cap is essential for producing a clean surface with a low-temperature heat cleaning.

The superlattice photocathode was fabricated by the molecular beam epitaxy (MBE) technique at NEC Fundamental Research Laboratories. One half of the photocathode was used for polarization measurements at Nagoya University and the other half was used in the high-charge extraction tests at SLAC.

A maximum polarization of 71% at a laser wavelength of 756 nm was observed with a Mott analyzer at Nagoya University [10]. The polarized source and Mott analyzer system at Nagoya is described in Reference [11]. The source routinely achieves a vacuum of 6×10^{-10} Torr. The superlattice cathode was installed in the gun, the gun baked, and then the cathode activated by heat cleaning for about 1 hour at $\sim$ 400°C to remove the arsenic cap. The cathode was then activated with cesium and oxygen to create an NEA surface. The QE at the wavelength corresponding to the highest polarization (i.e., at 757 nm) was measured to be 0.5% (1.0% at 752 nm) using an extraction voltage of 4 kV. The polarization and the QE as a function of a laser wavelength are shown in Figure 2.

The Gun Test Laboratory (GTL) at SLAC consists of (1) an SLC polarized gun, (2) a high-power Ti:sapphire laser that produces a single 2 ns pulse at 60 Hz, and (3) a duplicate of the first 2 m of the SLC beam transport system. The superlattice photocathode was first installed in the load lock in the GTL, and then heat cleaned as described above for the Nagoya measurement. After the NEA activation, the crystal was placed in its running location at the cathode electrode of the polarized electron gun where the vacuum is 2×10^{-11} Torr. The QE as measured at 1 kV with a low-power CW diode laser was 1.79% (1.08 mA at 100 μW) at 752 nm and 0.026% (29 nA at 169 μW) at 833 nm. All quantum efficiency measurements were made at room temperature with 14 mm diameter laser spots centered on the photocathode.

The gun was then configured for running at high voltage. The QE at 752 nm was measured at cathode potentials between 1 and 120 kV. It was observed to rise with increasing voltage, reaching 2.0% upon attaining 120 kV (corresponding to a gradient at the photocathode surface of ~ 2.7 MV/m). The results are plotted in Figure 3. The QEs measured at SLAC are higher than those observed at Nagoya, probably due to the better vacuum and the use of a load lock system for introducing the cathode into the gun after the bake of the gun chamber and after HV processing.

The Ti:sapphire laser was tuned to 757 nm with a spectral width of ± 1.5 nm. The pulses were 2 ns wide full width half maximum (FWHM) and 3 ns long at the base. The laser spot size was made larger than the 20 mm diameter active area of the photocathode thus insuring full cathode illumination. The energy of the laser pulses was controlled via a Pockels cell with a maximum of 40 μJ per pulse incident onto the photocathode. The current out of the photocathode was measured with a nanoammeter that was mounted inside the gun's high-voltage corona shield and which sensed only the current flowing to the cathode structure. The dark current as measured by this nanoammeter was 25 nA.

The response of the photocathode to the illumination of the 757 nm pulsed laser over a large range of laser pulse energy is shown in Figure 5(a). In the low-energy regime, the photoresponse of the cathode is linear with a slope characteristic of the QE. The QE evaluated from this slope is approximately 1.3%, which is understandably smaller than the value measured with the 752 nm diode laser, since the spot size of the pulsed laser was made larger than the cathode itself to ensure full illumination, and also because of the slightly longer wavelength. As the laser energy increases above $\sim 5\ \mu$J, the response quickly saturates and becomes quasilinear at higher energies. The maximum charge of 2.3×10^{11} electrons/pulse is actually larger than the value expected for a 2 ns pulse in the space-charge-limited case, which is about 1.8×10^{11} electrons/pulse based on an EGUN simulation [12]. This apparent contradiction is resolved when the temporal profile of the electron pulse is examined.

Figure 5(b) shows the temporal profiles of the charge pulses measured with a fast wall-gap current monitor located at 1 m downstream from the cathode for four different laser pulse energies: 1, 3, 11, and 39 μJ, respectively. It is noted that the charge pulses have about the same width as the laser pulse (i.e., about 2 ns) for the two cases of lower energies, but become broadened for the two cases of higher energies (i.e., in the saturated regime). This behavior is in contrast to the cathode charge limit phenomenon for which the charge pulse becomes increasingly narrower with increasing laser energy. The peak amplitude of the charge pulse increases with laser pulse energy in the unsaturated regime, but remains constant in the saturated regime. The quasilinear increase in the charge in the saturated regime in Figure 5(a) is due to the broadening of the charge pulse. The FWHM of the charge pulse due to the laser pulse of maximum energy is 2.5 ns. Scaling back to the nominal 2 ns FWHM, the charge associated with this pulse becomes 1.8×10^{11} electrons/pulse, consistent with the space charge limit. Alternatively, by extrapolating to zero laser energy from the quasilinear data set in the saturated regime in Figure 5(a), one also arrives at a value of about 1.8×10^{11} electrons/pulse, again in agreement with the space charge limit. Thus, it is shown that the maximum charge extractable from this cathode is consistent with the space charge limit. This exceptional charge performance is attributable to its remarkably high QE. Of course, when the QE drops below a critical value, the cathode charge limit rather than the space charge limit of the gun is expected to become the limiting factor in determining the maximum extracted charge. We did not attempt to identify the critical QE value for which the charge-limit effect begins to set in.

We have also not measured the intrabunch charge limiting effects for this cathode, but since the doping concentration at the surface is very high, such effects are expected to be minimal [5].

In summary, we have tested a superlattice photocathode with an active layer thickness of 95 nm for charge and polarization characteristics. We obtained a high charge of 2.3×10^{11} electrons in 2.5 ns for an excitation wavelength of 757 nm and a high quantum efficiency of 2.0% measured at a laser wavelength of 752 nm. For this high QE, the cathode charge limit effect was not observed. With a duplicate crystal, we measured a polarization of 71% at a wavelength of 756 nm and a corresponding QE of 0.5%. Thus the GaAs–AlGaAs superlattice cathode holds promise for providing high intensity pulses of highly polarized electrons over a wide range of quantum efficiencies. These properties may be crucial for future colliders.

References

[1] See, for example, "JLC–I," KEK Report 92–16 (1992); and C. Ahn et al., "Opportunities and Requirements for Experimentation at a Very High Energy e^+e^- Collider," SLAC Report–329 (1988).

[2] R. Alley et al., "The Stanford Linear Accelerator Polarized Electron Source," SLAC–PUB–6489 (1994), to be published.

[3] The measurement was made at high energy using the SLD Compton polarimeter for a charge of about 4×10^{10} electrons per bunch at the source, and a QE of $\sim 0.1\%$ measured at the polarization peak (845 nm) at 0°C. Similar results were obtained at low-energy for a duplicate cathode, using a Mott polarimeter in the laboratory and a low-intensity cw beam.

[4] The Stanford cathode is based on sample (5) of T. Maruyama et al., Phys. Rev. B46 (1992) 4261; see also Reference [10], below.

[5] M. Woods et al., J. Appl. Phys. 73 (1993) 8531; and H. Tang et al., "Experimental Studies of the Charge Limit Phenomenon in NEA GaAs Photocathode," SLAC–PUB–6515 (1994), contributed to the 4th European Particle Accelerator Conference, 27 June–1 July, 1994, London, England.

[6] T. Omori et al., XVth International Conference on High Energy Accelerators, Int. J. Mod. Phys. A (Proc. Suppl.) 2A (1993) 157.

[7] Y. Kurihara et al., KEK Preprint 90–77 (1990).

[8] Y. Kurihara et al., Nucl. Instrum. and Methods, A313 (1992) 393.

[9] This photocathode has the same structure as sample (e) of ref.[6].

[10] Mott polarization measurements made at SLAC and at Nagoy a with thin GaAs crystals from the same wafer, and prepared with a similar QE, resulted in polarizations of 43.3% and 46.4%, respectively. The discrepancy is attributable to calibration differences between the Mott polarimeters.

[11] T. Nakanishi et al., Phys. Lett. A158 (1991) 345.

[12] EGUN is a computer code for electron optics and gun design. See W. Herrmannsfeldt, SLAC Report–331 (1988).

Figure Captions

1. The structure of the superlattice photocathode.
2. (a) The polarization of electrons, and (b) the quantum efficiency versus laser wavelength measured at Nagoya University.
3. High voltage dependence of the quantum efficiencies measured at 752 nm and 833 nm.
4. Typical pulse shape of the laser pulses.
5. (a) Charge saturation curve and (b) pulse shapes of extracted electrons measured with a fast wall-gap monitor at laser pulse energies of 1, 3, 11, and 39 μJ (60 Hz).