PROCEEDINGS OF SCIENCE

Development of Polarized Electron Sources in Japan

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Future particle accelerator projects in Japan such as the proposed International Linear Collider and an upgrade under consideration to the SuperKEKB collider plan to utilize spin-polarized lepton beams. Work is underway to create robust sources of polarized electrons for these projects, as well as solving issues related to beam transport and spin manipulation. Here we describe the work being done to meet the challenges spin-polarized beams in current and future generation accelerators in Japan.

20th International Workshop on Polarized Source, Targets, and Polarimetry (PSTP2024)
22-27 September 2024
Jefferson Lab, Newport News, VA

ISSN 1824-8039 . Published by SISSA Medialab.

https://pos.sissa.it/

1. Introduction

Dating back to the 1980's, Japanese laboratories have been at the forefront of polarized lepton source development. Following the observation that bulk GaAs could produce selectively polarized beams of electrons, Nakanishi [1] and Maruyama [2] showed in 1991 and 1992, respectively, that the fraction of polarized electrons could be increased to greater than 50%, previously thought to be the limit. Since then, further developments in polarized electron sources have continued to emerge, including further increases in polarization by the implementation of compensated strained superlattice structures in GaAs [3,4]. Negative Electron Affinity (NEA) thin-film surfaces applied to GaAs cathodes to improve electron yields have also been improved upon, increasing both the lifetime and quantum efficiency (QE) of polarized sources.

To meet the needs of both modern and future accelerator facilities intending to utilize polarized beams, research into the development of more robust, longer-lived polarized cathodes with high rates of polarization and QE has been ongoing. Here we discuss the mechanism of polarized beam generation from GaAs, a selection of efforts at improving the lifetimes of cathodes and their possible future uses at projects and facilities in Japan.

1.1 GaAs as a polarized electron source

In this section we discuss briefly the mechanism for production of polarized electron beams from a GaAs cathode and the improvement of polarization rates by improvements in the material structure.

GaAs is known as a direct band-gap semiconductor, meaning that the top of its valence band and bottom of its conduction band coincide, in this case at the Γ(000) point with a band gap of 1.42 eV. Furthermore, the valence band at this point is composed of two degenerate bands with differing selection rules for excitation to the conduction band. Application of a circularly polarized laser can preferentially pull electrons from one particular band, resulting in a polarized beam; however, the degeneracy in bulk GaAs prevents polarization rates greater than 50%. Figure 1 shows a detail of the area around the Γ point, with the degenerate bands labeled 'Heavy holes' and 'Light holes'.

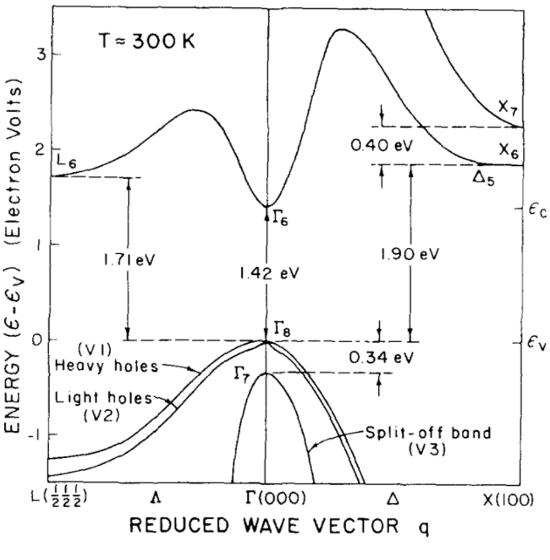

Figure 1. Band structure of bulk GaAs around the Γ(000) point [5]

Introduction of a dopant such as P can introduce a strain in the lattice which serves to break the degeneracy of the bulk material, introducing a small

(~0.5 eV) gap which allows for greater preferential selection. Further improvements, such as alternately layering doped and undoped GaAs and the addition of a thicker base layer to compensate for strain relaxation lead to a compensated strained superlattice material, with polarization levels above 90% possible.

1.1.1 The NEA mechanism

A drawback to the introduction of strain into the GaAs lattice is a corresponding reduction in QE. The application of a thin film of alkali material with a conduction band bottom below that of GaAs, normally Cs-O, serves to increase the electron yield from the GaAs by lowering the potential barrier of the vacuum. Cs-O, however, is chemically active and prone to degradation from ion back bombardment, chemical poisoning and thermal desorption, limiting the useful lifetime of NEA cathodes. Short-lived cathodes require frequent changing, resulting in the loss of beamtime, and therefore development of more robust cathodes which can also maintain their QE and polarization rates is a priority for the polarized electron community.

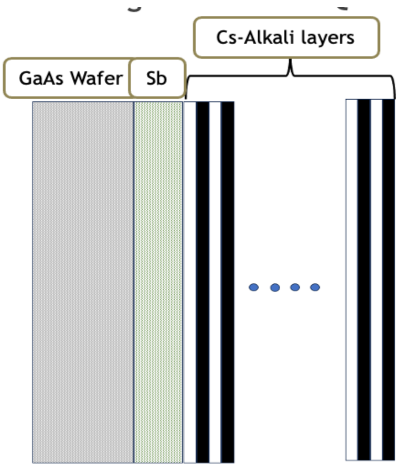

Figure 2 Example of a heterojunction cathode consisting of alternating thin layers of Cs-Alkali (e.g., Cs-K) deposited atop a Sb base layer

1.1.2. Development of improved NEA cathodes

In 2011, Sugiyama [6] proposed using Te instead of O along with Cs based on experience with Cs_2Te cathodes. Further improvements have come in the form of heterojunction cathodes consisting of a compensated strained superlattice GaAs wafer with an NEA film composed of multiple alkali metals, e.g. Cs-K, along with a semiconductor such as Te or Sb. Subsequent tests of such heterojunction cathodes have reported cathode lifetimes improved by an order of magnitude or more [7].

Despite such reported improvements, material compositions of cathodes as well as recipes for their production have yet to be fully optimized. Layering of NEA cathode material, thicknesses of each individual layer, and deposition order can play a large role in the determination of the cathode's properties, including QE and lifetime. Ongoing work to optimize these quantities for various novel NEA surfaces and measure their respective characteristics is ongoing, e.g., [8,9].

1.2 Current and proposed uses of polarized lepton beams in Japan

The International Linear Collider (ILC), proposed to be built in Iwate, Japan, has a physics program which includes polarized lepton beams as a part of its base design [10]. The ILC Technical Design Report calls for polarization greater than 80% with a QE of at least 0.5%, both of which are feasible with existing cathodes; however, improvement of cathode lifetimes to minimize beam downtime is of crucial importance. The high peak current of 3.2 A and bunch repetition rate of 1.8 MHz will contribute to thermal desorption of the NEA surface, necessitating an even more robust cathode.

In addition to the ILC, a current proposal under consideration to extend the physics program and lifetime of the SuperKEKB facility and Belle II experiment at KEK, in Tsukuba, Japan, is the addition of a polarized electron beam [11]. As a shorter-term proof-of-concept, a minimal version involving only the installation of a polarized source and associated spin-manipulation magnets in the SuperKEKB source area has been proposed by the Polarization Working Group. Such an experiment would verify the generation and transport of electrons to the interaction point in the main storage ring, making use of a slight (~1%) difference in intrabeam (Touschek) scattering backgrounds between polarized and unpolarized states [12] to make measurements without the need for spin rotators or Compton polarimetry. The Belle II Background Group has already demonstrated the ability to measure backgrounds at this level [13,14], making the demonstration feasible. The full polarization program would then follow at later stages in SuperKEKB's lifetime. While outside the scope of this paper, further details can be found in Reference [10].

While colliders are likely the most well-known uses of polarized beams, other applications exist, notably in polarized electron microscopy [15].

1.3 Outlook

The increasingly challenging environments in particle accelerators resulting from higher luminosities and beam currents planned for modern and future facilities necessitate ever-more robust cathodes. Work in Japan to meet these challenges has been ongoing for several decades, with consistent improvements in GaAs lattice structure and more recently, NEA surface development to provide electron sources capable of meeting the requirements of such facilities. Experimentation and optimization of known recipes, as well as ongoing searches for novel solutions to these challenges are ongoing and aim to continue the history of innovation of polarized sources in Japan.

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