Seminar II: Spin-polarized electron production

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Abstract

As of today, photocathodes based on Gallium Arsenide (GaAs) are the only option available for electron guns to produce the spin polarized electron beams required by the Electron Ion Collider and other novel techniques. However, these materials still possess some limitations: as bulk materials the Electrons Spin Polarization (ESP) is theoretically restricted to 50%, and in practice to around 35%. The ESP can be increased above 90% using strained structures. Yet, the Quantum Efficiency (QE), relatively high (10%) for bulk material, is drastically lowered for strained structures to 1% or less. Additionally, photocathodes are extremely vacuum sensitive and prone to be easily damaged, limiting the operational lifetime. In order to improve the structure of today's cathodes and look for other materials that could replace GaAs, a deep understanding of the mechanism that allows the material to produce the beam is necessary. In this report, we aim at detailing such process. The photoemission, spin depolarization mechanisms, and the activation process of GaAs bulk crystals will be explained in a conceptual approach. Therefrom, we are building a basis on which future investigations will be able to study new materials that could surpass today's photocathodes capabilities.

Contents

1 Overview

GaAs photocathodes as a source for spin polarized electrons was first proposed in 1974. To characterize a polarized beam, there are 3 important parameters: quantum efficiency $QE = \frac{\#\text{electrons}}{\#\text{photons}}$, which is the proportion of extracted electron from injected photons; spin polarization $SP = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$, which as the name suggest gives the percentage of preferential polarization; and lifetime $1/\tau = ln(\frac{QE_O}{QE})/t$, which gives a sense of the amount of usable time for a photocathode. The first experiments with GaAs were able to obtain a 40% SP and 10% QE from bulk crystal using circularly polarized light, where the handedness of the light polarization determined the sign of the spin polarization.[1] As the understanding of electron emission was deepen, experiments were able to obtain better results.

In 1991, a paper was presented in which 70% polarization was achieved straining the lattice structure of GaAs with In, and later with P. The degeneracy of the heavy and light hole bands at the Γ point that causes the limitation of polarization to 50% can be removed by creating a pseudomorphic strain, growing a single heterojuntion of InGaAs on GaAs substrate, and such creating a lattice mismatch.[2] Researched continued, and the cutting edge photocathodes produced today are based on a publication from 2016, where 100% is in theory principle, although it is limited experimentally to roughly 90%.[3]

Typically, the process of production is described with a three-step model. The first part is the photoexcitation, where electrons are excited into the conduction band and conservation of angular momentum leads to theoretical predictions of maximum polarization. Then comes the transport within the material, where numerous factors can depolarize the beam. Finally, electrons must leave the material, overcoming the work function at the surface through tunneling; this is the last step known as emission. This whole process takes place at a photocathode, usually mounted inside an electron gun under high vacuum conditions. After the electrons have been collected arrangements of electric fields lead the beam to the actual experiment.[4] Usually that means colliding the beam in order to obtain information about either the target or the beam itself.

Two important research that needs spin polarized electron beams include the Spin-Polarized Low-Energy Electron Microscopy (SPLEM) used at Berkeley National Laboratory to study film surfaces and interphases, and the Electron Ion Collider (EIC) to be build at Brookhaven National Laboratory which will study the internal structure of neutrons and the details of gluon interactions.

2 Excitation

When a material is irradiated with photons, the electrons in the atoms that compose it will get excited. The photon energy, as well as the energy level of the electron, will determine the final state of the electron. Some materials, like GaAs, have demonstrated to have preferential spin orientation at the conduction band when excited with particular photon energies. We can use this property to create beams of electrons with a desired polarization.

Each level of energy with corresponding momentum position within the crystal lattice is called a band. There are 3 minimum for the conduction band, where the lowest level, Γ, corresponds also to the highest point of the valence band, and the difference between these two determines the intrinsic energy band gap $E_g = 1.42$eV. Because of spin-orbit interactions, GaAs has two valence bands at the Γ valley, one four-fold degenerate and the other two fold degenerate, while the conduction band is only two-fold degenerate.[5] The valence band are called heavy hole (hh) and light hole (lh), and split-off (so) respectively, and the difference in energy between the hh and lh with the so band is called the split-off energy $\triangle_{so} = 0.34$eV.[4] Each one of these bands have angular momentum of $\pm 1/2$ or $\pm 3/2$. When you irradiate the material with circularly polarized light of energy hv corresponding to $E_g \leq hv \leq E_g + \triangle_{so}$ (which is equivalent to saying light of wavelengths between 700nm and 900nm approximately), since the angular moment of the light is ± 1, sign dependent of its helicity, it follows from conservation of angular momentum that the available states for the electrons are restricted.[5] This restriction results in a preferential spin state at the conduction band with ratio $2:1$ and the prediction of 50% theoretical polarization as depicted in figure 1.

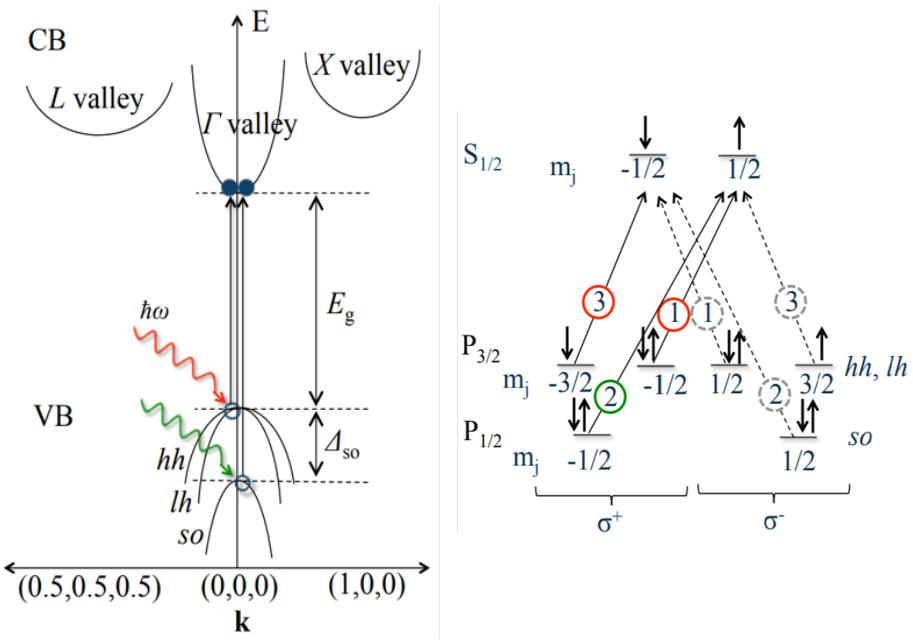

Figure 1: Right: Band structure of GaAs. Left: Excitation transitions for electrons from the valence band to conduction band of GaAs with corresponding electron angular momentum, where the circled numbers are the Glebsch-Gordan coefficients.

3 Transport

After the electrons are excited to the conduction band, unless they are literally at the first atomic layer, they have to travel a distance from their atom of origin to the surface. During this path, they can loose their spin polarization, or said otherwise, they can get depolarized. Different mechanisms exist to describe depolarization, and we divided them into momentum relaxation and spin relaxation mechanisms. Calculations and experiments situate the spin polarization lifetime in the order of $10^{-}8$s to 10^{-10}s, the specific depending on temperature and doping concentration.[6]

3.1 Momentum relaxation

There are numerous possible momentum scatterings, but for GaAs crystals the most relevant are lattice scattering, ion-impurities scatterings and electron-hole interaction scatterings. The lattice scatterings, also known as phonons, are vibrations of atoms that lead to displacements from their equilibrium crystal position. If atoms vibrate along the same direction, these are called acoustic phonons since it is like a "sound" moving through the material. When the atoms within a unit cell vibrate in opposite directions, it is called an optical phonon. They are called optical because these displacement can be generated using infrared light for some crystals. Both the ion-defect scattering and electron-hole interaction scatterings are via Coulomb-like interactions. Momentum relaxation by electron–hole interactions is different from Coulomb scattering by fixed charges (ionized impurities) in that the masses of electrons and holes are both finite and comparable, both carrier types drift in the electric field, and both types of carriers are able to screen the interaction.[7][4]

3.2 Spin relaxation

There are three main mechanisms that explain spin depolarization in GaAs, the Elliott-Yafet (EY), the D'yakonov-Perel (DP), and the Bir-Aronov-Pikus (BAP) mechanism. The first one says that because the original generated spin states are not 100% pure, there is always a probability that it will spontaneously change its state after any momentum scattering event. Because it occurs after momentum scattering events, its spin relaxation time is proportional to the total momentum relaxation. At small energies, EY is determined by ion impurity interactions, while intervalley

scatterings are most relevant at high energies. The DP mechanism stipulates that the spin of electrons precess between collisions around an effective magnetic field caused by the lack of inversion symmetry, or more simply put, the difference in energy between the spin up and spin down states causes precession of the original state. DP is the dominant mechanism at low dopant concentrations and high temperatures. Finally, the BAP mechanism says that the spin state of electrons can be "switch" with that of holes, and it is the dominant mechanism at room temperature and small electron energies in p-type GaAs.[4][6]

4 Emission

At the band edge, that is, the interface between the material and the vacuum, there is a potential barrier that stops electrons from escaping the material that is called the electron affinity. For pure GaAs, this corresponds to roughly 4eV. In order to allow electrons to escape more easily, GaAs crystals are doped with electropositive elements (p-doped), and before being used, fully grown cathodes undergo a process called "activation" that creates a negative electron affinity (NEA) coating over the surface. It should be noted that the exact nature and structure of the surface barrier is not well understood, and that even after both processes the way electrons escape to vacuum is due to tunneling. For the p-doping, the most commonly used dopant is Zn with doping concentration of 10^{-19}cm^{-3}.[4]

For the activation, the most commonly used elements are Cs and O. Cathodes of GaAs are grown under high vacuum conditions (between 10^{-10}Pa to 10^{-12}Pa), and are only exposed to air after their use. Right before putting to use a photocathode, Cs is allowed to circulate in the chamber and the cathode is heated to 550 C for 2-3 hours. Once it cools down, a laser is directed towards the cathode until a current is produced, after the current reaches its peak, O is introduce and the current will decrease. Once it is around 30-50% of the first peak, the O flow is reduced and allowed to reach a second peak higher than the previous one, at which point the flow is increased again and the current goes down once again. The process is repeated several times until a stable beam is achieved, and a graph of the current as a function of time is detailed in figure 2. After this process the photocathodes can be used continuously or at intervals with its lifetime determined by the vacuum conditions. It has been shown that low doping and low temperatures are the optimal conditions for these materials, with which the 50% theoretical polarization has been reported.[8]

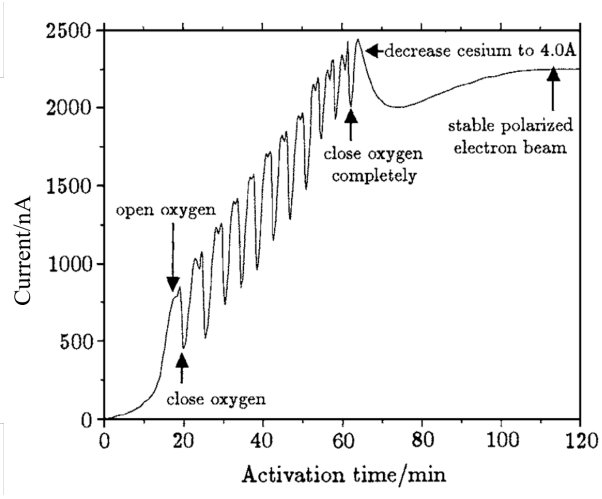

Figure 2: Beam current produced by the GaAs during the activation process. The time before the current was initiated is not included.

5 Current research

Since electrons have a very tiny size, they can be used to probe into molecules and even nucleons (protons and neutrons). Particularly, a spin polarized beam allows to investigate magnetic and fundamental properties. In particular,

two important projects that need polarized electron beams are the Spin-Polarized Low-Energy Electron Microscopy (SPLEEM) and the Electron Ion Collider (EIC).

The EIC is the next big accelerator facility that the Department of Energy of United States is planning to construct. It will be build at Brookhaven National Laboratory on top of the current RHIC facility by 2030. It will collide protons and atoms with polarized electrons to study the internal dynamics of nucleons and better determine gluon interactions. In order to comply with the proposed experiments, the required beam needs to have at least 80% polarization.[9]

The technique behind SPLEEM, designed and employed at Berkeley National Laboratory, was originally developed between Germany and IBM Almaden Research Center back in 1991. This machine allows imaging the magnetic microstructures at surfaces and interphases of thin films with good spatial and angular resolution, giving the user control of the spin polarization as well as the energy of the electrons. Note that the minimum energy has to be above the material work function, typically between 4-5 eV, or else the beam gets totally reflected. Probing the unoccupied electronic states of the material in an analogous way to a Fabry-Perot interferometer, beams reflected at the vacuum/film interface and at the film/substrate interface interact with each other, giving rise to constructive or destructive interference fringe. Up-to-date, it has been used: to investigate spin reorientation transitions in Ni/Cu(001) ultrathin films and Fe nanowires self-organized on W(110) surfaces, to study micromagnetic configurations and bistability phenomena in Co dots grown on Ru(0001), and to explore magnetic couplings in ferromagnetic/antiferromagnetic/ferromagnetic layered structures, respectively. Two examples are shown in figures **??** and **??**. Spin-polarized scanning tunneling microscopy is another technique used for the same purpose which allows to see the magnetism in materials down to the atomic scale and it uses the same principle of probing materials with electrons of known spin polarization.[10]

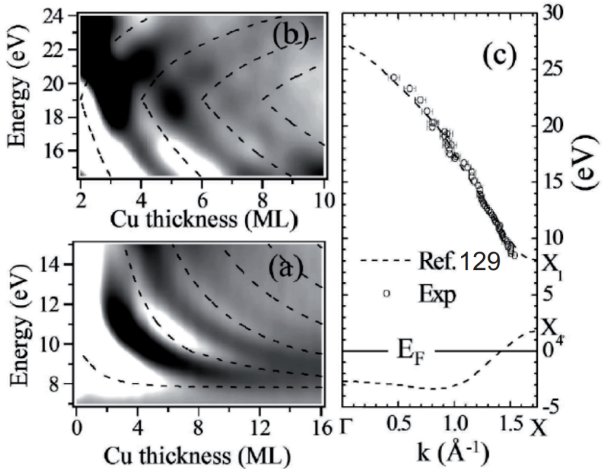

Figure 3: Left: Electron reflectivity (bright = high, dark = low) as a function of incident electron energy and thickness. Right: The band structure derived from oscillations of the reflectivity. It is dependant of spin orientation and local direction of magnetization.

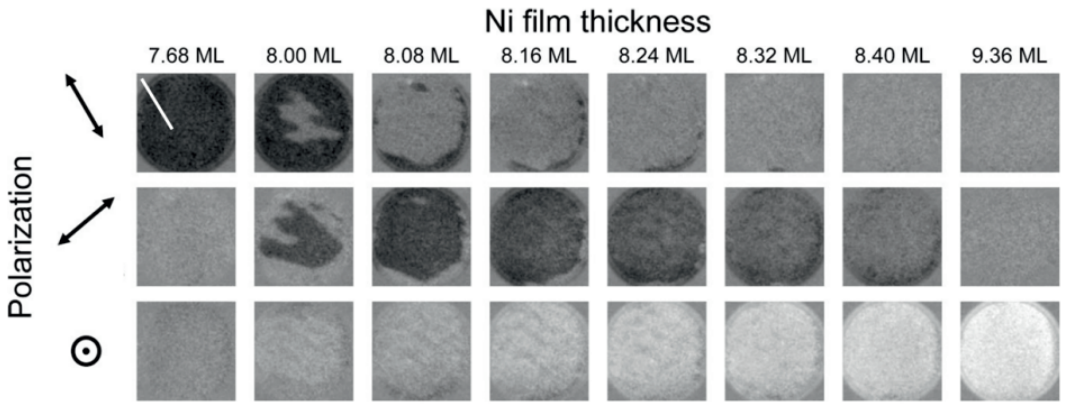

Figure 4: Several maps of the surface magnetization vectors for Nickel with 3 orthogonal components and different thickness. Dark or bright is corresponding to large vector magnetization, while grey is low.

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