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Experimental study on the activation process of GaAs spin-polarized electron source*

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GaAs spin-polarized electron source is a new kind of electron source, where the GaAs semiconductor crystal is used as a photocathode under the irradiation of helicity light. In this paper the activation process of the GaAs spin-polarized electron source is investigated experimentally in detail, during which the negative electron affinity of the photo cathode should be achieved more carefully by absorbing the caesium and oxygen on the surface of the GaAs crystal under ultrahigh vacuum conditions. Besides the different activation processes, the important physical parameters are studied to achieve the optimum activation results. At the same time the stability and lifetime of the polarized electron beam are explored for future experiments. Some important experimental data have been acquired.

Keywords: spin-polarized electron source, negative electron affinity, activation process
PACC: 2925B, 7280E, 8220P

1. Introduction

GaAs spin-polarized electron source was developed in the late 1970s,[1] in which the GaAs semiconductor crystal is used as a photocathode. During the activation process the caesium and oxygen can be absorbed on the surface of the GaAs crystal under an ultrahigh vacuum (UHV) condition to achieve the negative electron affinity (NEA). Then the circularly polarized laser with an appropriate wavelength is introduced to produce the spin-polarized electron beam. Compared with other electron sources, the spin-polarized electron beam produced by the GaAs photocathode has many advantageous features such as compactness, high-brightness, narrow-energy spread of the emitted beam, the possibility of modulating the beam intensity and easily changing the polarization directions, etc.[2] Based on these advantages, the GaAs spin-polarized electron source has been widely developed as a detection method in the areas of atomic and molecular physics, solid state physics, materials science, surface physics, nuclear physics and quantum chemistry.

However, it is extremely difficult to develop the GaAs polarized electron source because of its requirements of UHV (10^{-8}–10^{-9}Pa), special treatments of surface cleanliness achieved by chemical and heat methods, careful introduction of the caesium and oxygen to the vacuum chamber and complicated process of activation to gain a stable polarized electron beam. In this paper we investigate two different activation processes to produce the spin-polarized electron beam. Some important results have been obtained.

2. The principle of GaAs spin-polarized electron source

Three processes should be accomplished to produce a spin-polarized electron beam from the GaAs photocathode: (i) The electrons in the valence band should be excited to the conduction band by using photons with an appropriate energy, and the number of electrons with spin-up and spin-down must be different. (ii) The electrons in the conduction band should be transported to the surface of the GaAs crystal. (iii) The spin-polarized electrons should be emitted into the vacuum from the surface.

The GaAs crystal is a direct gap semiconductor with a minimum band separation of 1.42eV at room temperature near the centre of Brillouin zone, and its energy band structure along the axis of [111] and [110] is shown on the left-hand side of Fig.1.[2]

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Due to the spin–orbit interaction the valence band can be divided into fourfold degenerate $p_{3/2}$ levels and twofold degenerate $p_{1/2}$ levels, which have a separation of Δ=0.34eV. The $p_{3/2}$ levels have two sublevels: a heavy hole (hh) band with $m_j=\pm 3/2$ and a light hole (lh) band with $m_j=\pm 1/2$. The excitation process to produce spin-polarized electrons is explained on the right-hand side of Fig.1. The numbers in the circle are the relative transition intensities given by the Glebsch–Gordan coefficients. If the positive helicity light used here has the photon energy $E_g \leq \hbar\nu \leq E_g + \Delta$, the optical selection rules require that $\Delta m_j=+1$. Then the spin-down electrons are three times more than the spin-up electrons, and the theoretical spin polarization is

$$P = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = \frac{1-3}{1+3} = -50\%, \qquad (1)$$

where $N^{\uparrow}$ and $N^{\downarrow}$ are the numbers of electrons in the $m_j=+1/2$ and $m_j=-1/2$ states, respectively. Similarly, for the negative helicity light, P is 50%.

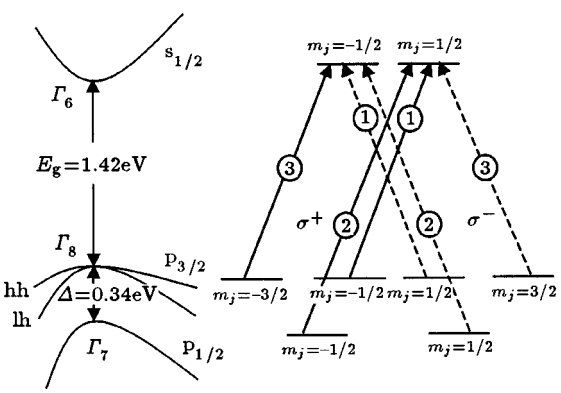


Fig.1. The band structures of the GaAs crystal and its photon excitation transitions.

When the electron in the valence band is excited to the conduction band, its energy would be approximately 4 eV below the vacuum level and could not escape from the GaAs surface. Therefore, the caesium and oxygen layer on the GaAs crystal surface must be introduced to achieve NEA, which can make it possible to lower the vacuum level at the surface below to the energy of the conduction band and let the electrons escape to vacuum easily. If all the electrons in the conduction band are emitted into the vacuum, the highest polarization of 50% can be achieved. However, the transportation process of thermal diffusion towards the GaAs surface has a strong effect of depolarization, which can decrease the polarization to less than 50%. Ordinarily, the experimental result of polarization may be ~27% when using the normal GaAs crystal, and the maximum polarization obtained is 43%.[3] But with the strained GaAs or GaAs-GaAsP super-lattice crystals, 70% polarization has been reported.[4,5]

3. Instrument configuration of GaAs polarized electron source

The configuration of the GaAs spin-polarized electron source is shown on the left-hand side of Fig.2 to produce polarized electron beam. The spin rotation coils and electron optical lenses are shown on the right-hand side, which can change the spin of the electron beam to the horizontal or vertical direction and transport it to the excitation point. The GaAs crystal and 90° deflector are in the chamber of UHV (10^{-8}–10^{-9}Pa), while the diode laser (with a wavelength of 820nm and photon energy of 1.516eV), Pockels cell and the collimation system are outside the chamber. The line-polarized light emitted from the diode laser can be changed to negative helicity or positive helicity using the Pockels cell inserted behind, and the collimation system can be used to adjust the laser directly to the GaAs crystal surface. The caesium and oxygen should be introduced to the UHV chamber to obtain the NEA surface. Pure caesium can be provided by heating caesium dispenser, and oxygen can be gained through very thin silver tube by heating it to about 600°.

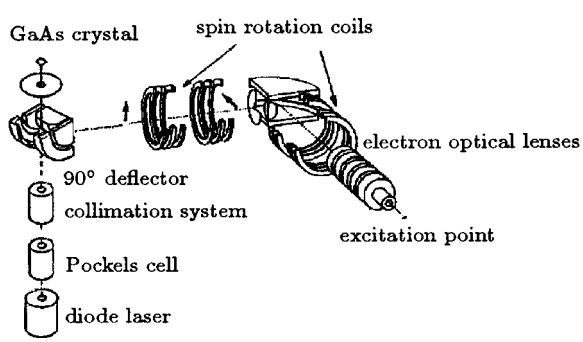


Fig.2. The instrument configuration of the GaAs spin-polarized electron source.

When the GaAs crystal is irradiated by the helicity light, the longitudinal-polarized electron beam can be produced with its moving direction opposite to the incident laser. After passing through the 90° deflector, the electron beam becomes transversely polarized. Then the electron beam is accelerated, focused and collimated by the electron optical lenses to the

excitation point to perform spin-resolve experiment.

4. The activation process of the GaAs polarized electron source

UHV (10^{-8}–10^{-9}Pa) in the chamber is necessary to gain a super clean GaAs surface and long lifetime electron beam. In addition to the vacuum obtained by turbo pump, ion pump and sublimation pump, the system should be cleaned more carefully with chemical and heating methods in sequence. After UHV is achieved, the apparatus is ready for the activation process. Generally, two steps should be carried out: (i) The heating cleanliness of the GaAs crystal. (ii) The physical activation.

4.1. The heating cleanliness of the GaAs crystal

In order to obtain a superclean surface, the crystal should be heated up to a temperature of 550°C±10°C for 2–3h. During the heating process the caesium dispenser is warmed up with a current of 4.0A and the silver tube at 300°C to accumulate certain caesium in the chamber with its vacuum better than 5×10^{-6}Pa to protect the GaAs surface from contamination. Then the heating process is finished and the temperature of GaAs crystal decreases naturally with the caesium heating current at 2.0A. When the temperature of the GaAs crystal cools down below 90°C, it is the right time to start the activation.

4.2. The physical activation of the GaAs crystal

The activation process is extremely important for the stability and long lifetime of the polarized electron beam, thus the optimum experimental parameters should be studied thoroughly.

For the first time of activation, a simple light source such as an electric torch may be appropriate to pour light on to the GaAs crystal surface because it is very difficult to focus the small diode laser beam on to it exactly. After some electron beam is obtained, the diode laser could be introduced with its position being adjusted by the precise collimation system to achieve the maximum electron beam current.

When the temperature of the GaAs crystal decreases below 90°C, the caesium current can be increased to 4.0–5.0A to start the activation. In our experiment it took 90–120min for the first appearance of electron beam. This time may vary significantly for different GaAs sources due to, e.g., the distance between the caesium dispenser and the GaAs crystal and the state of the caesium dispenser. At this time, different methods can be introduced to reach the saturation of the emitted electron beam. Presently three activation methods have been developed: yo-yo process, saturation process and compound process.[3] For the saturation process, the caesium and oxygen should be introduced to the chamber continuously to attain a maximum polarized electron beam. However, it is very difficult to gain a stable current beam for a certain system. Thus we emphasize for our experiments on the compound process and yo-yo process.

4.2.1. Compound activation process

A typical experimental result of the compound activation process is shown in Fig.3, where the wavelength of the laser is 820nm with its output power ~2mW. The voltages of Pockels cell are ±2900V to produce positive and negative helicity light respectively. The temperature of the silver tube is about 600°C and the caesium dispenser heating current is 4.8A. The starting time in Fig.3 is set at the first appearance of electron beam (~104 min from the beginning of activation). The compound process can be described as follows: during the activation the heating current of caesium dispenser is kept constantly, e.g., at 4.8A. When the polarized electron beam first appears, it will increase continuously to a peak value. Then oxygen is introduced by heating the silver tube to about 600°C. At this time the electron beam will increase a little and then decrease. When the electron beam reduces to 30%–50% of its first peak, the oxygen exposition is stopped by lowering the temperature of the silver tube below 350°C and the electron beam will increase again to the second peak, higher than the first one. The silver tube is then started again and the electron beam will increase a little and decrease. Also we wait until it reduces to 30%–50% of the second peak and then close the silver tube again. After a number of such cycles (~10, see Fig.3) there is a very little further increase of the peak value for the polarized electron beam. At this time the silver tube is stopped completely and the heating current of the caesium dispenser should be continued to decrease the electron beam by 10% of its last peak value, then the caesium current is decreased to 4.0A and is kept at this value later. In this way the electron beam will decrease a little to go into a more stable equilibrium

value (~2.250μA in Fig.3). The whole activation process lasts for 3.5h including the waiting time for the appearance of electron beam. In Fig.3 only the first cycle of opening and closing of oxygen are indicated, which is same for the other cycles. In addition to each peak, the electron beam will increase a little after oxygen is introduced, and then it will decrease rapidly. The reason is that it will take 1–2min to reach 600°C to produce oxygen for the silver tube, and at this time the caesium in the chamber is a little excessive, which can restrain the effect of NEA. When the oxygen is introduced, it will enhance the NEA effect to increase the polarized electron beam a little. But too much oxygen will kill the NEA greatly to decrease the polarized electron beam rapidly.

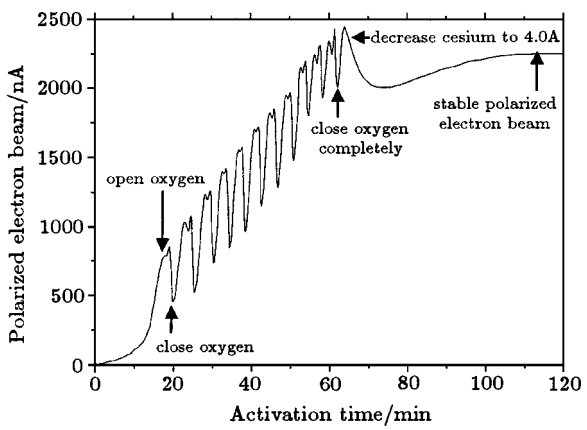


Fig.3. The compound activation process of the GaAs spin-polarized electron source.

4.2.2. Yo-yo activation process

In contrast with the compound activation process, both of the oxygen and caesium should be opened and closed periodically during the yo-yo process. When opening the oxygen, the caesium should be closed, and vice versa. And the other operations are the same as the compound process. A typical yo-yo process experimental result is given in Fig.4 with the caesium heating current being kept at 5.0A and the latency time for the appearance of electron beam lasts for 96min. The entire activation process lasts for 2.5h.

Comparing the yo-yo process with the compound process, the following differences can be seen: (i) In the yo-yo process, at each peak there is not enough NEA effect on the GaAs surface due to the absence of caesium in the chamber after opening oxygen and closing caesium, so the electron beam must suffer a little decrease for a while. When the oxygen is opened, though the NEA has some enhancement, the electron beam peak of oxygen is still lower than that of caesium peak just before, which is apparently different from the result of the compound activation process. (ii) The caesium heating current is 5.0A in the yo-yo process, which is a little higher than that (4.8A) in the compound process, thus its waiting time is comparatively shorter and increasing electron beam is more rapid. Furthermore, the first peak in the yo-yo process is a little higher than that in the compound process. (iii) Though the last peak in the yo-yo process is 3.100μA, it is only 2.450μA in the compound process, the decreasing rate in the yo-yo process is faster than that in the compound process. So the final stable polarized electron beam in the yo-yo process is 2.320μA, while it is 2.230μA in the compound process.

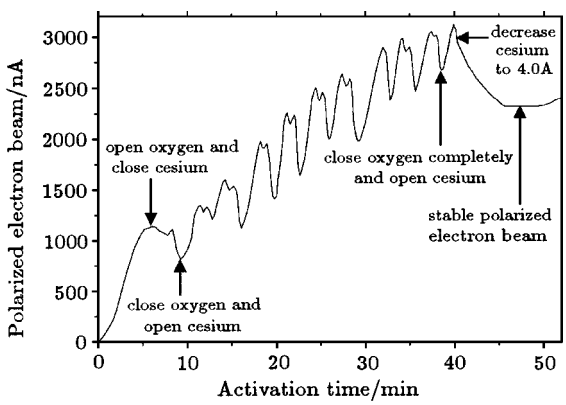


Fig.4. The yo-yo activation process of the GaAs spin-polarized electron source.

5. Discussion

From the experiments of the yo-yo activation process and compound activation process, we know that the UHV (10^{-8}–10^{-9}Pa) and cleanliness of the surface of the GaAs crystal are very crucial for this kind of polarized electron source. Also, the following aspects are concluded: (i) The NEA is an important factor to produce polarized electron beams from the GaAs surface. (ii) For NEA surface the amount of caesium should be appropriate in the vacuum chamber. If there is not enough caesium, the effect of NEA will be decreased more quickly than that with the excessive caesium in the chamber. (iii) The appropriate amount of oxygen is also significant for the NEA surface, but its effect is just contrary to that of the caesium. If the oxygen in the chamber is rare, its influence may be small. But excessive oxygen may have deadly influence so as to kill the NEA completely and decrease the polarized electron beam to zero. (iv) It is absolutely necessary to achieve a saturation of polarized

electron beam through several cycles with alternating applications of caesium and oxygen.

However, the most important objective for the spin-polarized electron source is to achieve the most stable electron beam with a longest lifetime. From many times of activation we have found that it is very difficult to gain a stable and long lifetime electron beam with only several times of activation. After the first activation, the electron beam is observed to decrease very rapidly. And with increasing activation times, the polarized electron beam becomes more and more stable. In our experiments at least more than ten times of activation have been performed to gain the stable polarized electron beam, which cannot only improve the cleanliness of the GaAs crystal surface, but also accumulate a useful amount of caesium in the vacuum chamber to enhance the NEA effect.

A longer lifetime is also achieved if the GaAs crystal is continuously exposed to some amount of caesium. Much time should be spent to optimize this parameter. In our experiment the optimum heating current for the caesium dispenser may be 4.0–4.2A. With this parameter and after ten times of activation, the polarized electron beam could last for several hundreds of hours with only a little decrease of the electron beam. If more times of activations are performed and the above parameters are optimized further, the spin-polarized electron beam with a lifetime of more than one thousand hours may be achieved, which would provide the most important detection method to perform the experimental research on spin-resolved effects during the collision and excitation processes between the spin-polarized electron beam and the atom or molecule.[6]

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