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Angular dependence of the photoelectron energy distribution of InP(100) and GaAs(100) negative electron affinity photocathodes

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Energy distribution of the photoelectrons from InP(100) photocathodes are investigated with a photon energy range from 0.62eV to 2.76eV. When the photon energy is less than 1.8eV, only electrons emitted from the Γ valley are observed in the energy distribution curves (EDC). At higher photon energies, electrons from the L valley are observed. The angular dependence of the electron energy distributions of InP and GaAs photocathodes are studied and compared. The electrons emitted from the L valley have a larger angular spread than the ones from the Γ valley due to the larger effective mass of the L valley minimum.

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InP based negative electron affinity (NEA) photocathodes have recently been recognized as having important applications in near infrared (IR) transferred electron (TE) photocathodes.[1, 2] The energy and angular distribution of photoelectrons are very important for the performance of the devices based on such photocathodes because they directly affect the final image resolution of those devices. Extensive studies have been focused on the energy distribution of GaAs photocathode, which have been very useful in understanding the electron scattering and electron transport properties.[3-11] However, little published work has been focused on the angular distribution of the photoelectrons emitted from III-V photocathodes, especially InP based photocathodes which have great importance in current technologies.[12-15] In this work, we used energy distribution curve (EDC) measurements to investigate the electron transport and scattering in InP NEA photocathodes. We are able to identify the features associated with the Γ valley and the L valley of the conduction band. The Γ valley electrons are found to have a narrower angular spread than the L valley electrons for both InP and GaAs photocathodes.

The InP(100) and GaAs(100) samples used in this study are p-type, Zn doped with a hole concentration of 2.3×10^{19} cm^{-3} and 5.3×10^{18} cm^{-3}, respectively. They were purchased from Wafer Technologies, U.K. Chemical cleaning procedures developed earlier in our group are used to clean the InP(100) and GaAs(100) surfaces.[16-18] Cleaned

InP and GaAs are activated as photocathodes by Cs and oxygen.[19] Monochromatic light from 0.62eV to 2.76eV is provided by an ORIEL 250 W quartz halogen lamp system with an ORIEL Cornerstone 130 monochromator, which is operated with a resolution of 2.64 nm, equivalent to 13 meV at 500 nm. A small bias of -4 eV is applied to the sample so that the photoelectrons can be collected by the PHI hemispherical electron energy analyzer, which is operated with an energy resolution of 40 meV. All the EDC data are plotted using the kinetic energy of the electrons right after being emitted from the sample surface. The position of the electrons from the bulk conduction band minimum (Γ minimum) is marked as E_{CBM} and is determined by $E_k = h\upsilon - E_B - \Phi + \text{Bias}$, where Φ is the analyzer work function, and E_B is the "binding energy" of the conduction band minimum and is calculated to be -1.30eV based on the carrier concentration (it is negative because it is above the Fermi level).

Figure 1 shows the energy distribution curves of the InP photocathodes taken at different photon energies at normal emission. At a photon energy of 1.76eV, there is only one feature in the EDC. This feature corresponds to the electrons which are excited into and thermalize in the Γ valley, the lowest valley in the InP conduction band.[12] The low energy cutoff of the EDC, which represents the vacuum level, is below the bulk conduction band minimum in the bulk. This indicates that some electrons encounter further electron-phonon scattering in the band bending region (BBR) and lose energy there, a phenomenon also observed on GaAs and GaN photocathodes.[4]

At higher photon energies, a second feature with a peak at approximately 0.55eV is observed. The intensity of this feature grows with larger photon energies similar to what was observed on GaAs.[6, 10, 12, 20] This second feature is due to the electrons emitted from the L valley, the next lowest valley in the conduction band. We can see that the position of this L valley feature is lower than the energy of the L valley minimum in the bulk, which sits 0.59eV above the Γ valley minimum and is labeled as E_L in figure 1.[12] This is also believed to be caused by the energy loss of the L valley electrons in the band bending region as a result of electron-phonon scattering there. The lack of an X valley feature when the photon energy is above 2.2eV is due to the large coupling coefficient between the X and L valleys, which will cause the X valley electrons to relax into the L valley,[21-23] as discussed in published work on GaAs.[3-11] For the EDC taken at a photon energy of 1.85eV, which is lower than the energy required for electrons to populate the L valley in the bulk, we can still observe the existence of the L valley feature. We believe this is due to the inter-valley scattering in the band bending region. For p-type InP, bands bend down near the surface, so the energetic electrons in the Γ valley can have enough energy to be scattered into the L valley in the band bending region.[4]

Figure 2 shows the EDCs of an InP photocathode at different emission angles with 0^o as the normal emission angle. The L valley feature decreases more slowly at larger angles than the Γ valley feature. This difference in the angular dependence can be linked to the different effective masses of the two valleys based on the two selection rules for those electrons to escape: the preservation of the momentum parallel to the surface and the preservation of the total energy.[24, 25] Intuitively, the preservation of the parallel momentum makes the kinetic energy component parallel to the surface ($E_{//}$) smaller after emission because the effective mass (m^*) is smaller than the free electron mass (m_o). The loss of the parallel energy will be transferred to the energy component perpendicular to the surface ($E_\perp$), which is the so-called "focusing effect." According to the mathematical model formulated by Zhi et al., the smaller the effective mass m^* is, the narrower the angular spread will be.[25] The L valley of InP has a larger effective mass ($0.25m_o$) than the Γ valley ($0.062m_o$), so it has a larger angular spread.

As shown in figure 2, the low energy cut-off of the EDC moves to higher energy when the emission angle becomes larger. This is because only the energy component perpendicular to the surface can help the electrons to escape from the surface. For those electrons emitted from an off-normal angle, the total energy is higher because it includes the component parallel to the surface.

As a comparison, the angular dependence of the electron energy distribution of the GaAs photocathode is also studied. The electron energy distributions of a GaAs NEA photocathode at different emission angles are shown in figure 3. The Γ and L valley features can be clearly identified in the EDCs, as reported in earlier publications.[6, 10, 12, 20] Compared to InP, the separation between the Γ valley and the L valley features of the GaAs photocathode is smaller. This is because the energy difference between the Γ valley minimum and the L valley minimum for GaAs is 0.29 eV, much smaller than that of InP (0.59eV). From figure 3, we can see that the angular dependence of the EDCs of the GaAs photocathode behaves similar to InP. The Γ valley electrons show a smaller angular spread due to the smaller effective mass, while the low energy cut-off moves to higher energies at larger emission angles because only the energy perpendicular to the surface can help the photoelectrons to escape.

In summary, the Γ valley and the L valley features are identified in the photoelectron energy distribution of InP NEA photocathodes. For both InP and GaAs photocathodes, the L valley electrons are observed to have a larger angular spread than the Γ valley electrons because L valley has a larger effective mass. For those devices which require very high resolution, the Γ valley electrons can be selectively chosen because of the narrower angular distribution.

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Figure Captions

Figure 1. Electron Energy distribution curves of InP photocathode taken at different photon energy with normal emission angle. All spectra are normalized by the number of photons. The x-axis is the kinetic energy of photoelectrons emitted from the sample surface. The energy for the electrons from the conduction band minimum is marked as $E_{CBM.}$

Figure 2. Electron Energy Distribution Curve of InP photocathode at different emission angles with 500 nm (2.46 eV) light excitation. The x-axis is the kinetic energy of photoelectrons emitted from the sample surface. The energy of the electrons from the conduction band minimum is marked as $E_{CBM.}$

Figure 3. Electron Energy Distribution Curve of a GaAs photocathode at different emission angles with 500 nm (2.46 eV) light excitation. The x-axis is the kinetic energy of photoelectrons emitted from the sample surface. The energy of the electrons from the conduction band minimum is marked as $E_{CBM.}$

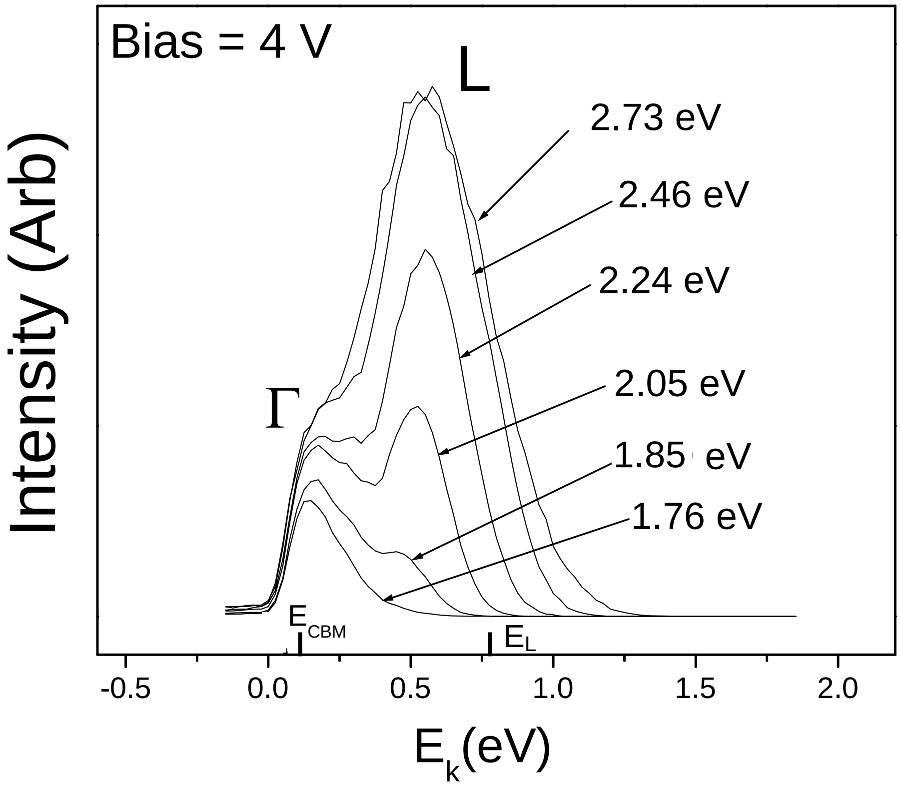

Figure 1

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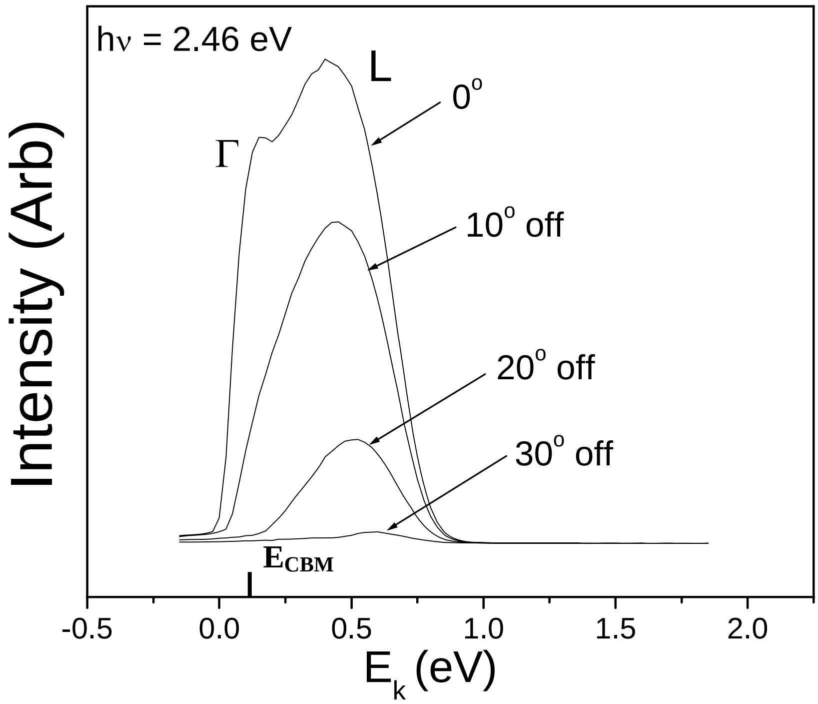

Figure 2

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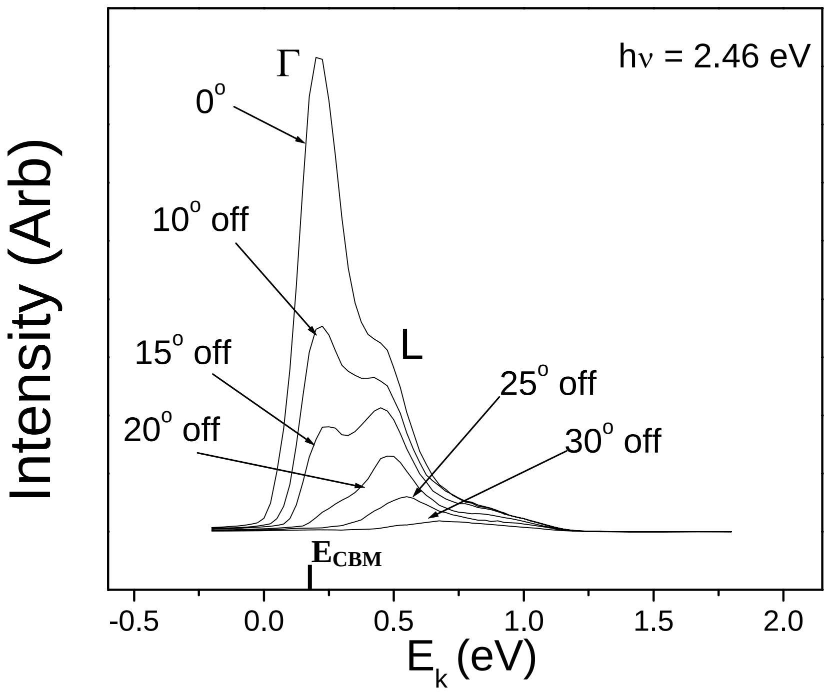

Figure 3

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