Strain and quantum confinement play an important role in tuning the valley degeneracy in indirect bandgap semiconductors. Two dimensional electron systems (2DESs) as well as one dimensional systems (1D) in AlAs have been previously studied and analyzed for (001)-oriented quantum wells (QWs), both of which have a reduced valley degeneracy from the bulk. The 2D systems are seen to have an isotropic mobility resulting from doubly degenerate valleys with orthogonally oriented anisotropic masses. But the other facets of growth, like the (110)-oriented QWs have not been extensively explored. The knowledge of the doping efficiency for this orientation is necessary to grow optimally doped cleaved-edge overgrown quantum wires and the valley degeneracy is expected to be different from (001)-oriented wells. In this paper, we present an experimental study of a doping series of double-sided-doped QWs grown in (110)-orientation and show experimental evidence of single-valley occupancy and an anisotropic electron mass for these QWs. This has been further complemented with effective mass calculations with finite barrier that take strain into account, which explain how for (110)-oriented AlAs QWs, single-valley occupation is expected for the square well width \( W > 53 \text{ Å} \). Also, we deduced the donor binding energy and the doping efficiency. Previously, anisotropic single-valley systems have only been investigated in piezo-strained (001) AlAs samples. In contrast, the (110) AlAs samples investigated in this Letter are singly-degenerate as a result of the growth orientation, require no additional piezo sample preparation to reach single-valley occupancy, and tend to show higher mobilities than those reported in piezo-strained samples.
rection and the QW width \( W \) due to a balance of strain and confinement effects. For (001)-oriented QWs studied elsewhere with \( W < 55 \, \text{Å} \), a single X-valley is occupied whereas \( W > 55 \, \text{Å} \) yields doubly-degenerate occupied X-valleys in the QW. 

We determine in this work how (110) QW valley degeneracy should depend on well width. The energy \( E_\tau (k) \) of an electron in a valley \( \vec{x}_\tau \) with index \( \tau \) (\( \tau = x, y, z \)) is

\[
E_\tau (k) = E_{\text{kin}} (k) + E_{0, \tau} + \Delta_\tau (k)
\]

where \( E_{\text{kin}} \) is the in-plane kinetic energy, \( k \) is the 2D in-plane momentum relative to the \( \tau \)-valley minimum, \( E_{0, \tau} \) is the ground confinement energy, and \( \Delta_\tau \) is the strain induced energy shift at the Brillouin zone edge at the X-point. It is useful to introduce the cubic crystal axes \( \vec{x} = (x, y, z) \) and the growth axes \( \vec{a} = (a, b, z) = R \vec{x} \) related by the rotational transformation (Fig. 1)

\[
R = \begin{bmatrix}
\frac{1}{\sqrt{2}} & -\frac{i}{\sqrt{2}} & 0 \\
\frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\
0 & 0 & 1
\end{bmatrix}.
\]

Confinement energies are best determined by transforming the mass tensor to the growth-basis \( \vec{a} \). In the crystal-basis \( \vec{x} \), the mass tensor \( (m_{\vec{x}})^{-1} \) for the \( \tau \)-th valley is diagonal with \( m_{\tau}^{x} = m_{1} \) and \( m_{\tau}^{y} = m_{4} \) for \( \tau \neq \tau \). Transforming to the growth-basis \( \vec{a} \), the mass tensor becomes \( (m_{\vec{a}})^{-1} = R (m_{\vec{x}})^{-1} R^{-1} \), so for the \( x_{\tau} \)-valley, for example with \( \tau = x \)

\[
(m_{\vec{a}}^{x})^{-1} = \begin{bmatrix}
\frac{1}{m_{1}} & \frac{1}{m_{1}} & 0 \\
\frac{1}{m_{1}} & \frac{1}{m_{1}} & 0 \\
0 & 0 & \frac{1}{m_{4}}
\end{bmatrix}.
\]

with diagonal \( m_{d} = 2 \frac{m_{m} + m_{r}}{m_{m} + m_{r}} \) and off-diagonal \( m_{f} = 2 \frac{m_{m} m_{r}}{m_{m} + m_{r}} \) mass terms. The diagonal mass will enter into the Schrödinger equation for the quantum well confinement energy.

Deformation potential energies are best determined by transforming the strain tensor to the crystal-basis \( \vec{x} \). We assume that the AlAs QW \( (a_{\text{AlAs}} = 5.65252 \, \text{Å}) \) is strained relative to the GaAs substrate lattice \( (a_{\text{GaAs}} = 5.64177 \, \text{Å}) \) in agreement with previous publications.\(^{13,14,15}\) For (110) biaxial strain, the perpendicular component can be deduced from the in-plane strain as \( \epsilon_{\perp} = -D \cdot \epsilon_{||} \), where \( D = 0.6165 \) is a constant that depends on the interface orientation and on the elastic constants of AlAs.\(^{13,16}\) In the growth-basis \( \vec{a} \), \( (0, b, 0) \) is the growth direction, and the strain tensor \( \epsilon_{ij} \) is diagonal with \( \epsilon_{aa} = \epsilon_{zz} = \epsilon_{||} \), and \( \epsilon_{bb} = \epsilon_{\perp} \). Transforming to the \( \vec{x} \)-basis, the strain tensor becomes \( \epsilon = R^{-1} \epsilon R \) with diagonal terms \( \epsilon_{xx} = \epsilon_{yy} = \epsilon_{||} / \sqrt{2} \) and \( \epsilon_{zz} = \epsilon_{\perp} \).\(^{13,16}\)

The energy at the \( \tau \)-th valley minimum shifts from the unstrained case by an amount \( \Delta_{\tau} = \Xi \epsilon_{\tau \tau} \), where \( \epsilon_{\tau \tau} \) is defined in the crystal-basis \( \vec{x} \), and the deformation potential for AlAs is \( \Xi = 6.11 \, \text{eV} \).\(^{13}\) In our case, the single and double-degenerate X band edges are separated by 9 meV. Combining these new band edges with knowledge of the mass tensor, the Schrödinger equation can now be solved. All this information is automatically included in the publicly available simulation software nextnano\(^{3}(12)\) yielding a cross-over width \( W_{c} = 53 \, \text{Å} \).

For \( W > W_{c} \), there is only a single occupied in-plane valley shown in shaded grey in Fig. 1 inset. The two higher-energy out-of-plane valleys are shown as dotted ellipsoids. For \( W < W_{c} \) the role reverses, and these out-of-plane valleys become occupied. The projection of these valleys would be the white ellipsoids in the plane of the QW. Hence, the two valleys would have collinear longitudinal mass axes, in contrast to the (001) QW case where they are orthogonal.

Samples were grown on (110) GaAs substrates using molecular beam epitaxy. The structure of the samples is similar to the one discussed in Ref. 4 for the (001) facet and has been shown in Fig. 1. There is a 150 Å wide QW with three Si \( \delta \)-doping layers. \( \delta_{1} \) and \( \delta_{2} \) separated from the QW by Al\(_{0.45}\)Ga\(_{0.55}\)As spacers provide electrons to the QW. These two \( \delta \)-doping layers are doped equally with a Si density \( n_{\delta} = n_{G} = n_{Si} \). The Si doping near the surface has higher density \( n_{\delta} = 2.7n_{Si} \) and satisfies the surface states to pin the conduction band to the donor binding energy upon saturation. Various samples were grown with different doping \( n_{Si} \) indexed G through M.\(^{13,14}\)

Indium contacts were annealed at 450 °C for 100 s. Two-point contact resistance was around 100 kΩ at 300 K and around 40 kΩ at 4.2 K. Samples were illuminated using a red LED of wavelength 635 nm. We performed post-illumination anneal at around 25 K (PIA) for these samples, described previously for (001) AlAs samples\(^{4}\) to obtain persistent photoconductivity. Typical longitudinal \( (R_{xx}) \) and transverse \( (R_{xy}) \) resistance variation with magnetic field at 330 mK in the dark and post-illumination for sample J in van der Pauw geometry is plotted in Fig. 2. The density of the samples in subsequent figures were deduced from such measurements.

The first evidence of single-valley occupancy for (110)-orientation comes from the \( \nu = 2n + 1 \) periodicity at low magnetic field Shubnikov de Haas oscillations for the PIA data (Fig. 2 top). Due to the heavy cyclotron mass in AlAs, \( m^{\ast} = (m_{l}m_{t})^{1/2} \approx 0.47m_{e} \) and large Lande g-factor of \( g^{\ast} = 2 \) (Ref. 21), the bare Zeeman energy \( E_{Z} \) is about half the bare cyclotron energy \( E_{C} \), so that \( m^{\ast} g^{\ast} \sim 1 \) in the absence of interactions, the case shown in the Fig. 2 inset. Exchange and correlation enhancement of \( m^{\ast} g^{\ast} \sim 1 \) is known to occur in AlAs quantum Hall systems\(^{2,4}\), and for the range \( 1 < m^{\ast} g^{\ast} < 2 \), the Zeeman gap will be larger than the cyclotron gap and odd filling factor \( \nu = 2n + 1 \) will dominate at low fields. As shown in the data of Fig. 2 top, the odd integers clearly dominate \( \nu = 9 \) upwards and persist to filling factors as high as \( \nu = 33 \). In double-valley systems, by comparison, an additional factor of 2 appears in the filling factor due to valley degeneracy, and one observes prominent gaps in the series \( \nu = 4n + 2 \).
The density in both arms is found to be the same, \( n \) fabricated along the crystallographic axes \([001]\) and \([1\bar{1}0]\), and the mobility was found to be \( \mu'_{\text{VdP}} = 0.50 \times 10^5 \text{ cm}^2/\text{Vs} \). This is within reasonable agreement to the van der Pauw mobility, which is within 20\% of the average value. Comparing the \((110)\) results here with Ref. 2 which has an identical structure on the \((001)\) facet, we note approximately a factor of 6 reduction in van der Pauw mobility for the \((110)\) grown quantum wells. These results would be discussed in more detail in an upcoming publication.\(^2\)

The second evidence of single-valley occupancy comes from the anisotropic mobility in \((110)\) QWs. We performed mobility measurements on a \(L\)-shaped Hall bar fabricated along the crystallographic axes \([001]\) and \([1\bar{1}0]\). The density in both arms is found to be the same, \( n = 1.8 \times 10^{11} \text{ cm}^{-2} \) and \( \mu = 4.0 \times 10^4 \text{ cm}^2/\text{Vs} \) and post-illumination, \( n = 3.5 \times 10^{11} \text{ cm}^{-2} \) and \( \mu = 5.3 \times 10^4 \text{ cm}^2/\text{Vs} \). Inset on top shows the post-illumination longitudinal resistance for sample \( L \) at low magnetic fields. The odd periodicity of the prominent minima, is one indication of single-valley occupancy. The ladder diagram in the inset shows the Landau level splitting \( E_L \) and Zeeman splitting \( E_Z \) for \( g^*m^* = 1 \). The prominence of odd integer gaps suggests \( g^*m^* > 1 \) in the present system.

![FIG. 2: Typical \( R_{xx} \) and \( R_{xy} \) traces at 345 mK in the dark (dashed) and post-illumination (solid) for sample \( J \) in the van der Pauw configuration. In the dark, \( n = 1.8 \times 10^{11} \text{ cm}^{-2} \) and \( \mu = 4.0 \times 10^4 \text{ cm}^2/\text{Vs} \) and post-illumination, \( n = 3.5 \times 10^{11} \text{ cm}^{-2} \) and \( \mu = 5.3 \times 10^4 \text{ cm}^2/\text{Vs} \). Inset on top shows the post-illumination longitudinal resistance for sample \( L \) at low magnetic fields. The odd periodicity of the prominent minima, is one indication of single-valley occupancy. The ladder diagram in the inset shows the Landau level splitting \( E_L \) and Zeeman splitting \( E_Z \) for \( g^*m^* = 1 \). The prominence of odd integer gaps suggests \( g^*m^* > 1 \) in the present system.](image1)

![FIG. 3: The density of two dimensional electron system in a \((110)\)-oriented AlAs quantum well as a function of the Si delta doping \( n_{\text{Si}} \). The top \( x\)-axis defines the time of Si doping corresponding to the doping densities. The vertical dashed line shows the saturation threshold \( n_{\text{sat}} \) for both the dark and the post illumination(red LED \( \checkmark \)) conditions. The solid lines are plotted as an aid to locating the saturation threshold.](image2)
at the saturation threshold shown with a vertical dashed line. We define from Ref. 4,

\[ \eta_{DK,PIA} = \frac{n_{DK,PIA}}{2n_{Si}} \] (4)

where \( \eta \) is the doping efficiency. The factor of 2 in the denominator arises from the double-sided \( \delta \)-doping layers, assuming that all surface states have been screened by the top \( \delta \)-layer. Using this equation, we obtain the doping efficiency of \( \eta_{DK} = 7\% \) in the dark and \( \eta_{PIA} = 15\% \) post-illumination anneal.

In summary, we have shown experimentally the occupation of the single X-valley by the 2DES in AlAs QWs in this (110)-orientation, which shows anisotropic mobility that can be partly attributed to the mass anisotropy. We have also presented results of a model calculation for the cross-over width in AlAs for (110)-orientation, which defines the QW width below which double-valleys are occupied and above which a single-valley is occupied. Furthermore, we have determined the binding energy of Si in \( \delta \)-doped layers in Al\(_{0.45}\)Ga\(_{0.55}\)As in the dark and after illumination for the (110)-orientation and found them to be in the range of the values found for (001)-orientation. The doping efficiency for the Si \( \delta \)-layers has been calculated to be 7\% in the dark and 15\% post-illumination anneal. These parameters will be instrumental in optimizing mobility in (110)-oriented AlAs QWs and cleaved-edge overgrowth structures.

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18. G : 06-15-07.2, H : 06-15-07.1, I : 05-08-07.1, J : 05-08-07.2, K : 01-30-07.1, L : 01-05-07.2, M: 01-30-07.2
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