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Description	

# Strain-enhanced electron mobility anisotropy in $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$ two-dimensional electron gases

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## Abstract

We systematically investigated electron mobility anisotropy in compressively-strained, lattice-matched, and tensilely-strained InGaAs quantum wells (QWs) grown on InP(001) by using Hall-bar devices with various current-flowing directions. Anisotropy of electron mobility, the highest along [1-10] direction and the lowest along [110], is systematically observed in all QWs, and well-fitted with a sinusoidal function of the current-flowing direction angle. The mobility anisotropy is minimum in the lattice-matched case and enhanced by both compressive and tensile strains in the

QWs. We consider that random piezoelectric scattering, which is enhanced by the average normal strain in the QW, has anisotropy and plays an important role for the observed results.

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**Keywords:** InGaAs/InP; Two-dimensional electron gases (2DEGs); Strained quantum wells (QWs); Electron mobility anisotropy; Random piezoelectric (PE) scattering

## 1. Introduction

Two-dimensional electron gases (2DEGs) in InGaAs with high indium composition play an important role for high-speed device applications because of their very high electron mobilities and peak velocities. The 2DEGs in the InGaAs are usually obtained by means of pseudomorphic/lattice-matched (PM/LM) growth on InP(001) or metamorphic (MM) growth on GaAs(001). The 2DEGs in the MM InGaAs sometimes exhibit large anisotropy in electron transport such as higher mobilities along [1-10] direction and lower ones along [110] direction. While the anisotropy in the case of MM InGaAs on GaAs(001) had been attributed to anisotropic lattice relaxation, interface roughness or residual strain due to anisotropic cross-hatch morphology (CHM) [1], it was recently claimed that they cannot be the dominant origin of the anisotropy and indium composition modulation due to the anisotropic CHM is the most important origin [2]. However, in some cases there is no large mobility anisotropy ( $< 10\%$ ) even in the MM InGaAs with the anisotropic CHM [3]. In addition, large mobility anisotropy ( $> 15\%$ ) has been observed also in a PM InGaAs quantum well (QW) on InP(001) with neither lattice relaxation nor CHM [4]. These suggest a different origin of the mobility anisotropy with no relation to lattice relaxation or CHM.

In this work, we paid attention to strain in InGaAs QWs. We carried out PM/LM growth of InGaAs/InP heterostructures on InP(001) by metal-organic vapor phase epitaxy (MOVPE) in order to obtain high electron mobility 2DEGs in compressively-strained, lattice-matched, and tensilely-strained

InGaAs QWs. We systematically investigated the electron mobility anisotropy in the InGaAs QWs by using Hall-bar devices with various current-flowing directions.

## 2. Sample preparation

We grew 4 types of InGaAs/InP modulation-doped heterostructures for 2DEGs, 30 nm-InP / 10 nm-n-InP / 20 nm-InP / 10 nm-In<sub>x</sub>Ga<sub>1-x</sub>As / 300 nm-InP / InP(001) substrate, by MOVPE with N<sub>2</sub> carrier gas, trimethylindium (TMIn), trimethylgallium (TMGa), arsine (AsH<sub>3</sub>), phosphine (PH<sub>3</sub>), and disilane (Si<sub>2</sub>H<sub>6</sub>) at 670°C [5]. The differences in each growth are the partial pressures of TMIn and TMGa and the growth time for In<sub>x</sub>Ga<sub>1-x</sub>As.

After MOVPE growth, we carried out X-ray diffraction (XRD) and atomic force microscope (AFM) measurements of grown structures. Figure 1 shows (004) XRD measurement results with simulation curves. We confirmed the PM/LM growth of the heterostructures. By the simulation curves fitted to sub peaks from InGaAs, we also confirmed indium composition of  $x = 0.75, 0.62, 0.53$ , and  $0.44$  in In<sub>x</sub>Ga<sub>1-x</sub>As; InGaAs QWs of  $x = 0.75$  and  $0.62$  are compressively strained, that of  $x = 0.53$  is lattice-matched in average, and that of  $x = 0.44$  is tensilely strained. Figure 2 shows AFM images of the surfaces of grown structures. Very smooth morphologies with step-flows are observed. The roughness of each surface is less than 1 monolayer height in root-mean-square, and the directions of the step-flows are not related to crystal orientation. Thus, the step-flowing direction originates from substrate manufacturing, and almost smooth InGaAs/InP interfaces are expected.

For the investigation of the electron mobility anisotropy, we fabricated 6-terminal Hall-bar devices (50-μm-width and 200-μm-length) with 8 current-flowing directions by conventional photolithography techniques. Figure 3a shows an optical micrograph of the Hall-bar device. The current-flowing directions are defined by the angles from [1-10] direction as schematically shown in Fig. 3b.

## 3. Hall measurement results and discussion

We carried out Hall measurements of the Hall-bar devices at various temperatures with a He-flow

cryostat. At low temperatures less than 50K, evident anisotropy of electron mobilities are observed in each QW, while no anisotropy is observed in the higher temperature region. Figure 4 shows the electron mobilities at 10 K as a function of the angle from [1-10] direction or current-flowing directions. The data points and the error bars are determined by using the average and variations of sheet electron concentrations in 8 Hall-bar devices, respectively. The average values of the sheet electron concentrations are also shown in Fig.4, which slightly depend on indium composition. For fitting curves, we assumed the following Matthiesen-type equation;

$$\frac{1}{\mu(\alpha)} = \frac{1}{\mu_I} + \frac{\sin^2 \alpha}{\mu_A}, \quad (1)$$

where  $\alpha$  is the angle of the current-flowing direction from [1-10], and  $\mu_I$  and  $\mu_A$  are isotropic and anisotropic mobilities, respectively. Each curve is fitted well to the experimental data. Systematic anisotropy is observed in each QW, and the behavior is symmetric with respect to [1-10] direction. From XRD measurements, the anisotropy cannot originate from anisotropy of lattice relaxation. In addition, since step-flowing directions are not related to crystal orientation from AFM measurements, the anisotropy also cannot originate from anisotropy of interface roughness scattering.

Figure 5 shows the anisotropy parameter  $\mu_I/\mu_A$  as a function of indium compositions of InGaAs or lattice-mismatches of InGaAs with respect to InP.  $\mu_I$  and  $\mu_A$  are the fitting parameters in Fig.4. The result strongly suggests that the anisotropy of electron mobility can be enhanced by the lattice-mismatch between InGaAs and InP, or the strain in InGaAs QWs. Concerning the strain-relating modulation of the electron mobility, recently, an importance of random piezoelectric (PE) scattering in strained QWs has been pointed out [6]. In the case of zinc-blende structure, PE polarization is induced by shear strains. In ideal strained QWs, there is no shear strain resulting in no PE polarization. In contrast, in real strained QWs with imperfection, there are non-vanishing random shear strains, which are proportional to average normal strains. Therefore, the PE polarization takes place randomly in the real strained QWs with imperfection and scatters conductive electrons in QWs. The electron mobility anisotropy enhanced by the strain in InGaAs QWs can be attributed to the

anisotropy of the random PE scattering associated with the strain. Since a (001) surface of a zinc-blende structure has anisotropic nature between [110] and [1-10] directions, surface reconstruction and/or migration of III-group adatoms become anisotropic during III-V epitaxial growth. The anisotropy during growth can introduce anisotropic correlation length of randomness, which has been discussed in the case of 2DEGs in GaAs with extremely high electron mobilities [7]. In the case of 2DEGs in strained InGaAs QWs, the anisotropy of random PE scattering also can be caused by anisotropic correlation length originating from the anisotropy during growth. In addition, since As-P exchange at InGaAs/InP interfaces can result in weak normal strains causing non-vanishing random shear strains with imperfection, the electron mobility anisotropy even in the LM case can originate from the anisotropy of random PE scattering. In the case of the tensilely-strained QW ( $x = 0.44$ ), the electron mobility anisotropy seems larger than that in the compressively-strained QWs ( $x = 0.62$  and  $0.75$ ). Since the random PE scattering probability is increased with not only the strain but also the PE constant  $e_{14}$  and the effective electron mass  $m_e^*$ , large  $e_{14}$  and/or large  $m_e^*$  can be related to the origins of the larger anisotropy in the case of low indium composition  $x$ . It should be noted that a difference of the growth anisotropy also can affect the anisotropy of random PE scattering.

#### 4. Summary

In summary, we investigated the electron mobility anisotropy in PM/LM grown  $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$  QWs ( $x = 0.75, 0.62, 0.53$ , and  $0.44$ ) by using Hall-bar devices with 8 current-flowing directions. Although no lattice relaxation and no CHM are confirmed by XRD and AFM measurements, we observed the systematic anisotropy of electron mobilities in each QW by Hall measurements at low temperatures. The minimum anisotropy is observed in the LM case of  $x = 0.53$ . These results suggest that the electron mobility anisotropy can be enhanced by the strain in InGaAs QWs and attributed to the anisotropy of the random PE scattering associated with the strain. This is a possible origin of the electron mobility anisotropy which has been often observed in InGaAs QWs.

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### Figure captions

FIG. 1. X-ray diffractions of grown structures. Dots and curves indicate experimental data and simulation data, respectively.

FIG. 2. Atomic force microscope images of the surfaces of grown structures.

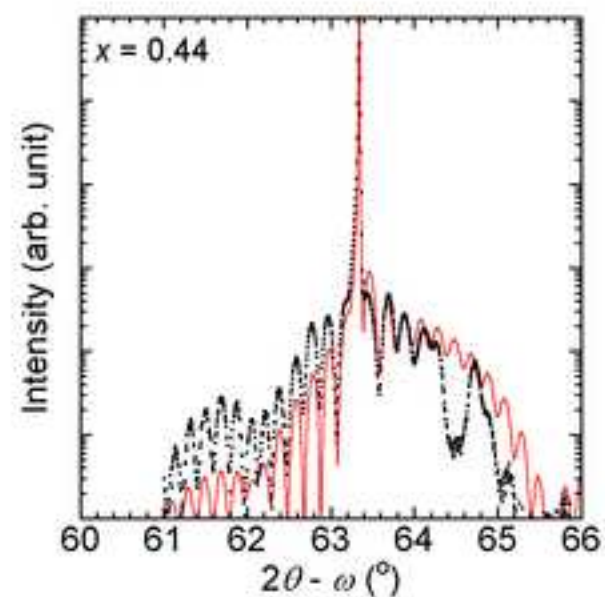
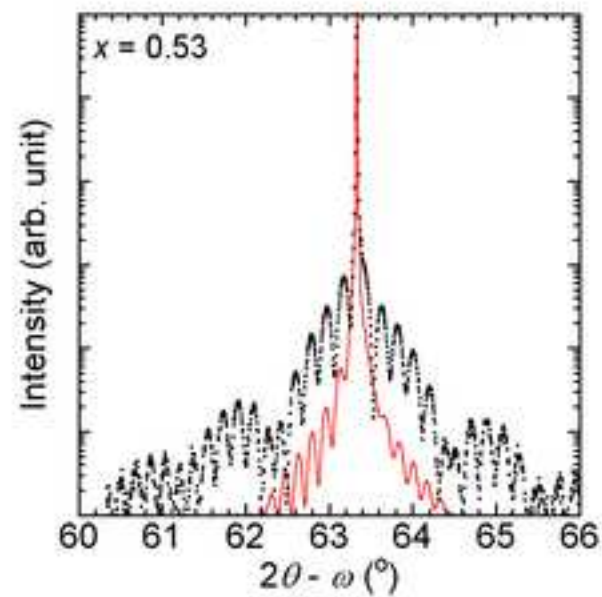
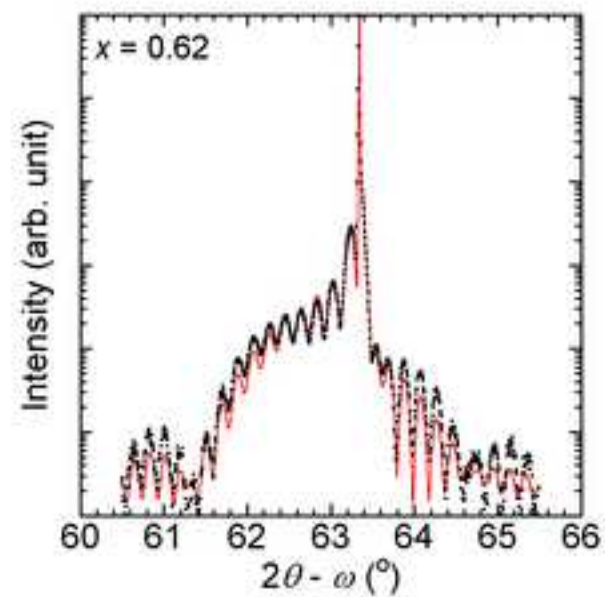
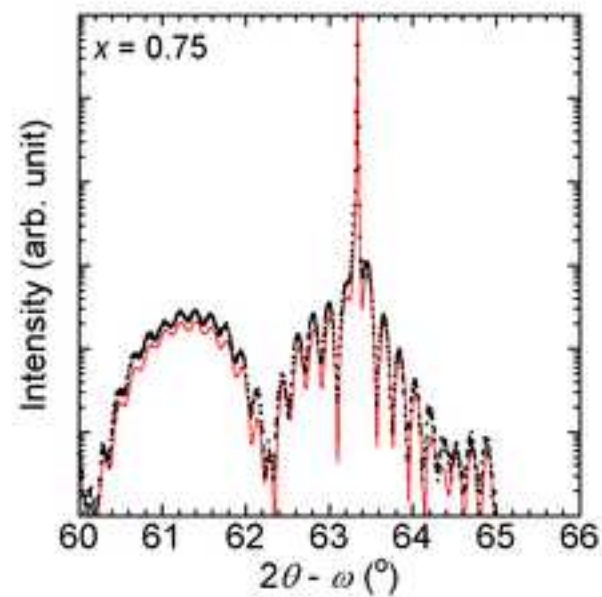
FIG. 3. (a) Optical micrograph of a Hall-bar device. (b) Current-flowing directions of Hall-bar devices.

FIG. 4. Electron mobilities at 10K as a function of current-flowing direction angles. Data points and the error bars are determined by using the average and variations of sheet electron concentrations in 8 Hall-bar devices, respectively. Solid curves are fitting results with assuming sinusoidal functions. The values of the sheet electron concentrations are also shown.

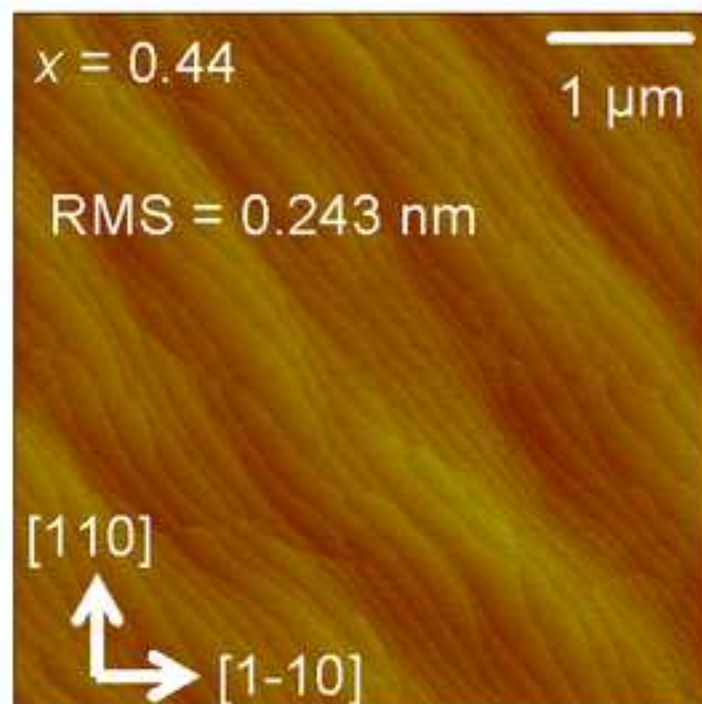
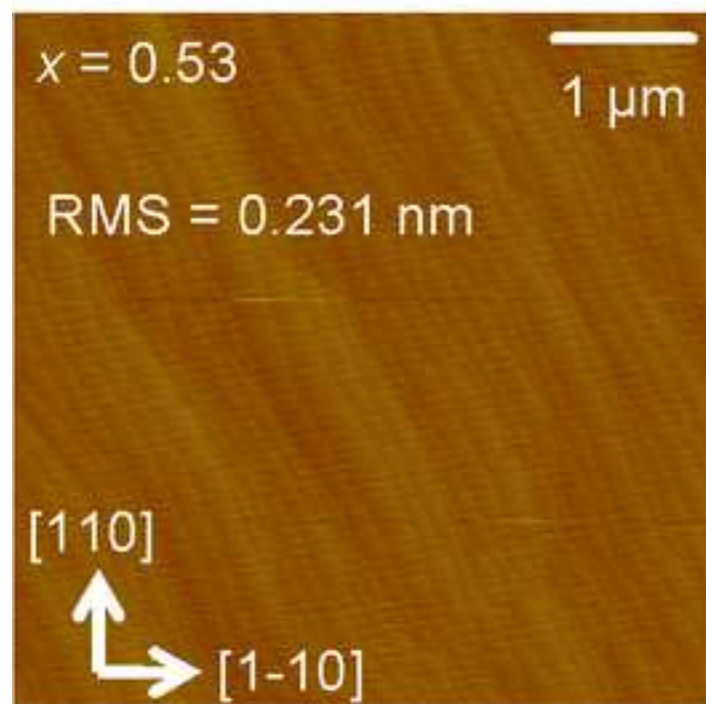
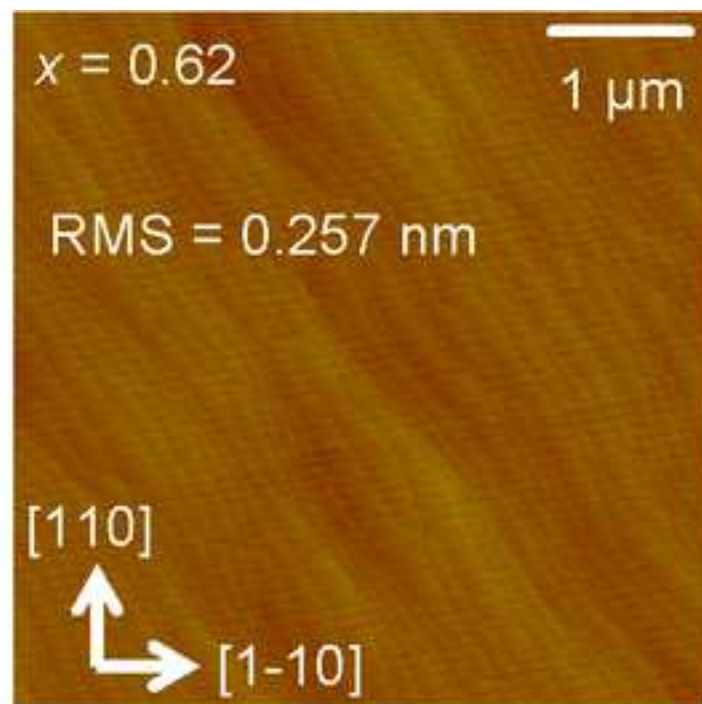
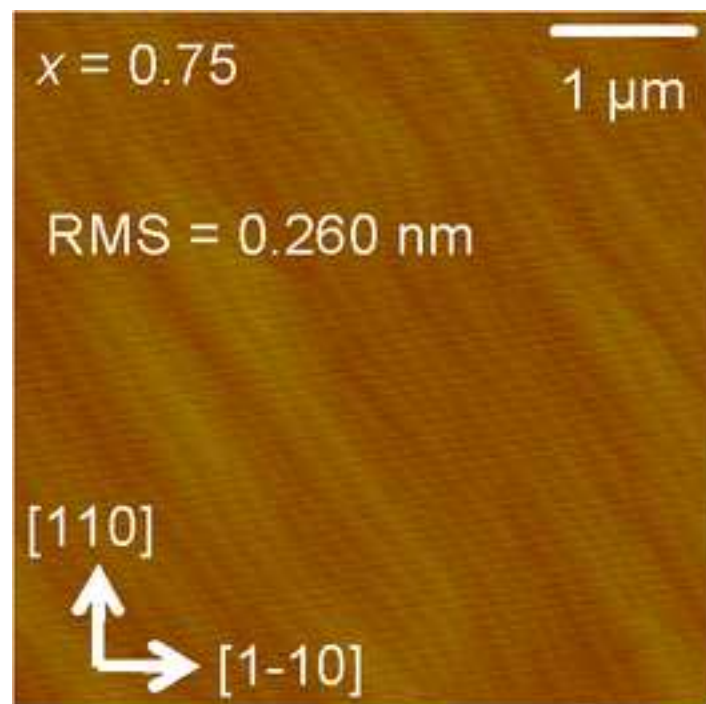
FIG. 5. Anisotropy parameter as a function of indium compositions of InGaAs or lattice-mismatches of InGaAs with respect to InP.



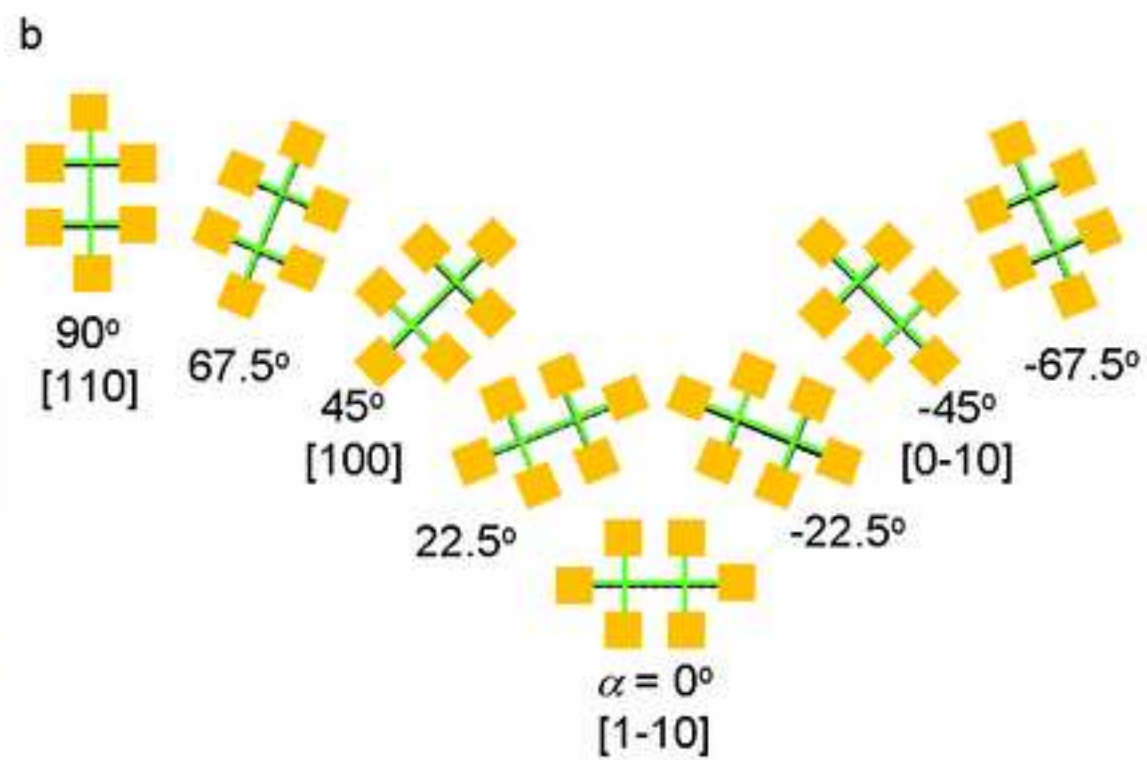
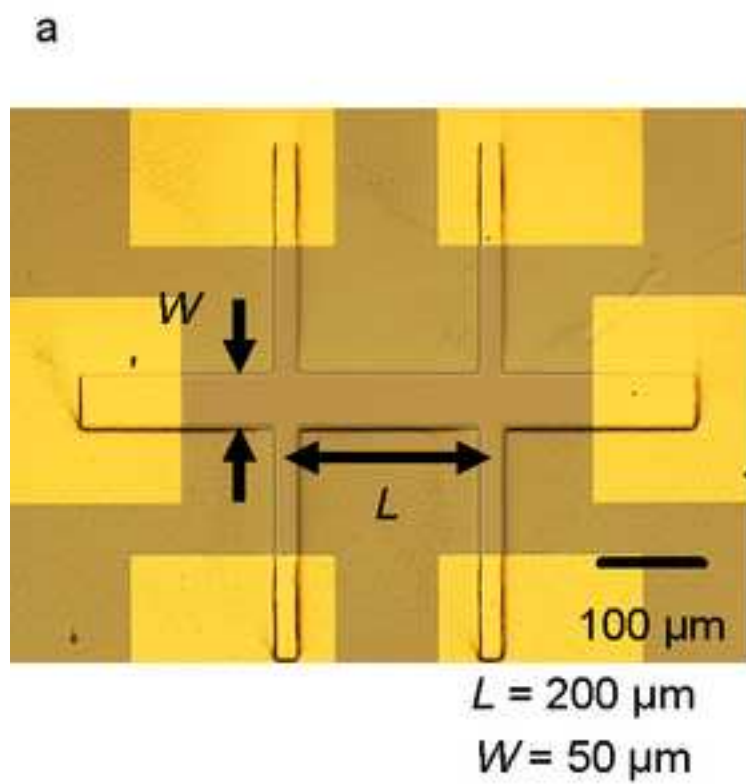
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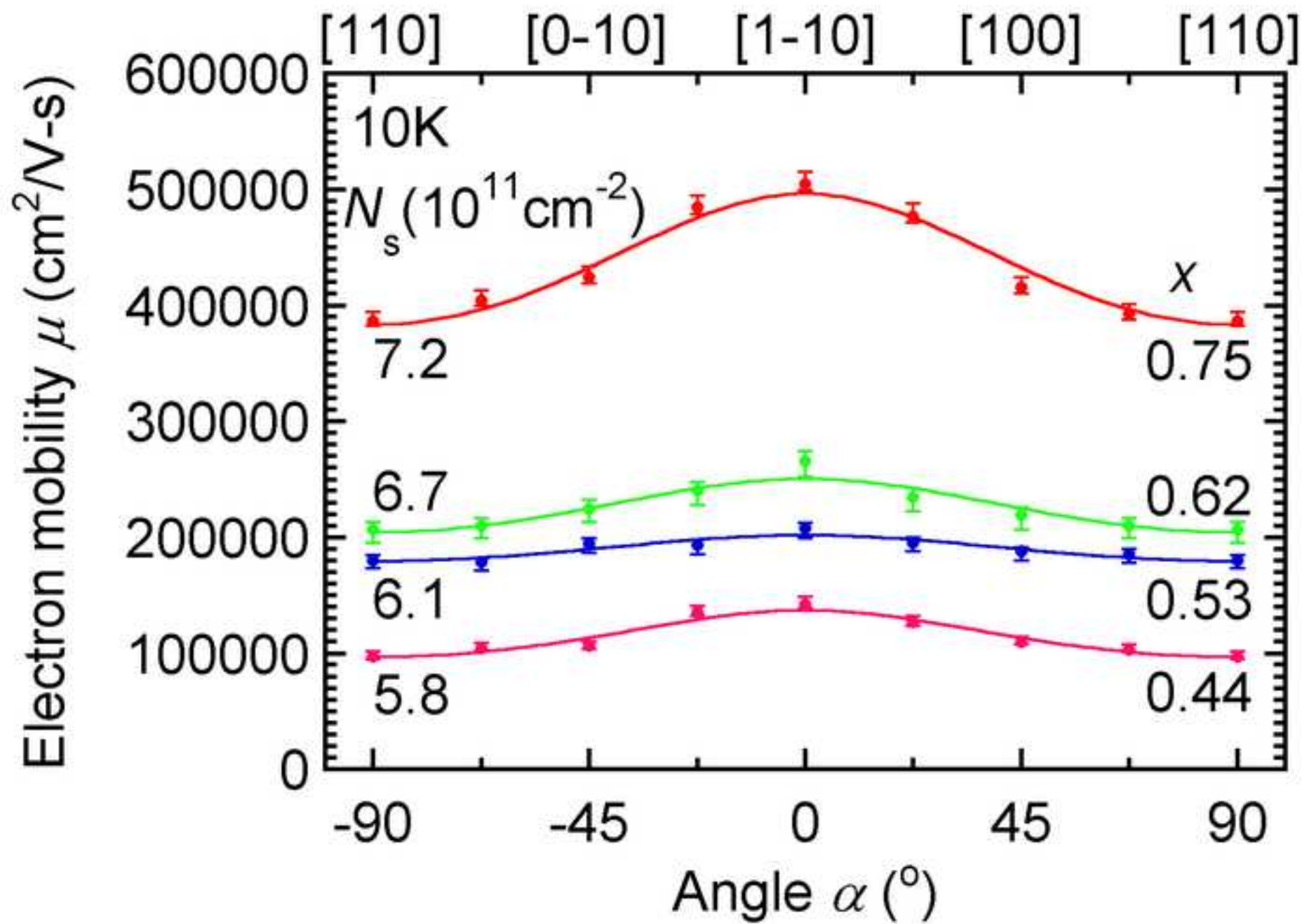
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