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Report Title

Development of Ultra Sensitive Piezoresistive Sensors Using AlAs 2D Electrons

ABSTRACT

The electronic properties of the two-dimensional (2D) electron systems in modulation-doped AlAs quantum wells are investigated, with the goal of developing this material as a sensor with an unprecedented, large sensitivity to stress and/or strain. Such a sensor may find use in various scanning probe microscopes, and in other applications where minute amounts of variables such as force, displacement, or pressure need to be measured.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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1. O. Gunawan, Y.P. Shkolnikov, E.P. De Poortere, E. Tutuc, and M. Shayegan, "Ballistic Transport in AlAs Two-dimensional Electrons," *Phys. Rev. Lett.* 93, 246603 (2004).
2. E.P. De Poortere and M. Shayegan, "A Hybrid Al_{0.10}Ga_{0.90}As/AlAs Bilayer Electron System," *Appl. Phys. Lett.* 84, 3837 (2004).
3. Y.P. Shkolnikov, K. Vakili, E.P. DePoortere, and M. Shayegan, "Giant Low-temperature Piezoresistance Effect in AlAs Two-dimensional Electrons," *Appl. Phys. Lett.* 85, 3766 (2004).
4. B. Habib, E. Tutuc, S. Melinte, M. Shayegan, D. Wasserman, S.A. Lyon, and R. Winkler, "Negative Differential Rashba Effect in Two-dimensional Hole Systems," *Appl. Phys. Lett.* 85, 3151 (2004).
5. B. Habib, E. Tutuc, S. Melinte, M. Shayegan, D. Wasserman, S.A. Lyon, and R. Winkler "Spin Splitting in GaAs (100) Two-dimensional Holes," *Phys. Rev. B* 69, 113311 (2004).
6. C. Gustin, S. Faniel, B. Hackens, S. Melinte, M. Shayegan, and V. Bayot, "Orbital Effect, Subband Depopulation, and Conductance Fluctuations in Ballistic Quantum Dots under a Tilted Magnetic Field," *Phys. Rev. B* 71, 155314 (2005).
7. E. Tutuc and M. Shayegan, "Interaction and Disorder in Bilayer Counterflow Transport at Filling Factor One," *Phys. Rev. B* 72 (Rapid Communications), 081307 (2005).
8. R. Winkler, E. Tutuc, S.J. Papadakis, S. Melinte, M. Shayegan, D. Wasserman, and S.A. Lyon, "Anomalous Spin Polarization of GaAs Two-dimensional Hole Systems," *Phys. Rev. B* 72, 195321 (2005).
9. Y.P. Shkolnikov, S. Misra, N.C. Bishop, E.P. De Poortere, and M. Shayegan, "Observation of Quantum Hall Valley Skyrmions," *Phys. Rev. Lett.* 95, 066809 (2005).
10. K. Vakili, Y.P. Shkolnikov, E. Tutuc, E.P. De Poortere, M. Padmanabhan, and M. Shayegan, "High-mobility Out-of-plane Valley Occupation in AlAs Quantum Wells," *Appl. Phys. Lett.* 89, 172118 (2006).
11. M. Shayegan, E.P. De Poortere, O. Gunawan, Y.P. Shkolnikov, E. Tutuc, and K. Vakili, "Two-dimensional Electrons Occupying Multiple Valleys in AlAs," (review article), *Phys. Stat. Sol. (b)* 243, 3629-3642 (2006).
12. O. Gunawan, Y.P. Shkolnikov, K. Vakili, T. Gokmen, E.P. De Poortere, and M. Shayegan, "Valley Susceptibility of an Interacting Two-dimensional Electron System," *Phys. Rev. Lett.* 97, 186404 (2006).
13. O. Gunawan, B. Habib, E.P. De Poortere, and M. Shayegan, "Quantized Conductance in an AlAs 2D Electron System Quantum Point Contact," *Phys. Rev. B* 74, 155436 (2006).
14. O. Gunawan, T. Gokmen, K. Vakili, M. Padmanabhan, E.P. De Poortere, and M. Shayegan, "Spin-valley Phase Diagram of the Two-dimensional Metal-insulator Transition," *Nature Physics* 3, 388-391 (2007). See commentary ("News and Views") by Jurgen H. Smet, "Metal-insulator Transition: A Plane Mystery," *Nature Physics* 3, 370-372 (2007).
15. O. Gunawan, E.P. De Poortere, and M. Shayegan, "AlAs 2D Electrons in an Antidot Lattice: Electron Pinball with Elliptical Fermi Contours," *Phys. Rev. B* 75, 081304 (2007).
16. B. Habib, J. Shabani, E.P. De Poortere, M. Shayegan, and R. Winkler, "Tuning of the Spin-orbit Interaction in Two-dimensional GaAs Holes via Strain," *Phys. Rev. B* 75, 153304 (2007).
17. B. Habib, J. Shabani, E.P. De Poortere, M. Shayegan, and R. Winkler, "Anisotropic Low-temperature Piezoresistance in (311)A GaAs Two-dimensional Holes," *Appl. Phys. Lett.* 91, 012107 (2007).
18. O. Gunawan, T. Gokmen, Y.P. Shkolnikov, E.P. De Poortere, and M. Shayegan, "Anomalous Giant Piezoresistance in AlAs Two-dimensional Electrons with Antidot Lattices," *Phys. Rev. Lett.* 100, 036602 (2008).

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1. J. Shabani, M. Shayegan, and R. Winkler, "Strain-induced Fermi Contour Anisotropy of GaAs Two-dimensional Holes," Phys. Rev. Lett. 100, IN PRESS (2008).

2. O. Gunawan, T. Gokmen, E.P. De Poortere, and M. Shayegan, "Characterization of the Anomalous Giant Piezoresistance in AlAs Two-dimensional Electrons with Antidot Lattices," submitted for publication.

Number of Manuscripts: 2.00

Number of Inventions:

Graduate Students

| <u>NAME</u> | <u>PERCENT SUPPORTED</u> |
|------------------------|--------------------------|
| Gokmen, Tayfun | 0.25 |
| Habib, Babur | 0.25 |
| Padmanabhan, Medini | 0.10 |
| Gunawan, Oki | 0.50 |
| FTE Equivalent: | 1.10 |
| Total Number: | 4 |

Names of Post Doctorates

| <u>NAME</u> | <u>PERCENT SUPPORTED</u> |
|------------------------|--------------------------|
| Gunawan, Oki | 0.50 |
| FTE Equivalent: | 0.50 |
| Total Number: | 1 |

Names of Faculty Supported

| <u>NAME</u> | <u>PERCENT SUPPORTED</u> | National Academy Member |
|------------------------|--------------------------|-------------------------|
| Mansour Shayegan | 0.25 | No |
| FTE Equivalent: | 0.25 | |
| Total Number: | 1 | |

Names of Under Graduate students supported

| <u>NAME</u> | <u>PERCENT SUPPORTED</u> |
|------------------------|--------------------------|
| FTE Equivalent: | |
| Total Number: | |

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

| | |
|--|------|
| The number of undergraduates funded by this agreement who graduated during this period: | 0.00 |
| The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... | 0.00 |
| Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... | 0.00 |
| Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: | 0.00 |

Names of Personnel receiving masters degrees

| <u>NAME</u> |
|----------------------|
| Total Number: |

Names of personnel receiving PHDs

| <u>NAME</u> | |
|----------------------|---|
| Habib, Babur | |
| Gunawan, Oki | |
| Total Number: | 2 |

Names of other research staff

| <u>NAME</u> | <u>PERCENT SUPPORTED</u> |
|------------------------|--------------------------|
| FTE Equivalent: | |
| Total Number: | |

Sub Contractors (DD882)

Inventions (DD882)

Development of Ultra Sensitive Piezoresistive Sensors Using AIAs 2D Electrons

**ARO Proposal Number 46433-MS
Agreement Number W911NF-04-1-0219**

**Final Report
February 14, 2008**

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I. Abstract

The electronic properties of the two-dimensional (2D) electron systems in modulation-doped AIAs quantum wells are investigated, with the goal of developing this material as a sensor with an unprecedented, large sensitivity to stress and/or strain. Such a sensor may find use in various scanning probe microscopes, and in other applications where minute amounts of variables such as force, displacement, or pressure need to be measured.

II. Final Report

II.1. Introduction

The piezoresistance effect, the change of a material's resistance as a function of strain is of great technological interest. (Strain, defined as the fractional change of a solid object's length, is a measure of the deformation of the solid under stress.) The effect is used to make piezoresistive sensors, devices that can measure important parameters such as force, displacement, and pressure. Such sensors are ubiquitous in industries such as construction engineering, process engineering, automobile, airplane, and other transportation vehicle engineering, and a variety of consumer goods. Even the semiconductor industry is using the piezoresistance effect to improve the performance of field-effect transistors. Recently, piezoresistivity is finding use in measurements of minute (~ 0.01 nm) displacements of tips in atomic force microscopes. With the advancements in science and technology of materials and devices whose size approaches the atomic scale, the interest in sensors that can detect ultra-small forces and distances is likely to grow even higher.

II.2. Piezoresistance of an AIAs two-dimensional (2D) electron system

The goal of this research project is to develop a new material, namely, the two-dimensional (2D) electron system in an AIAs quantum well, into a piezoresistive sensor that is far more sensitive than any piezoresistive sensor currently available. In our ARO-funded project we first showed that, at cryogenic temperatures, the gauge factor (fractional change of resistance divided by the fractional change in sample length) of an AIAs 2D electron system can exceed

10,000. This is 5,000 larger than the gauge factor for conventional metal wire/foil strain gauges, and about 10 times larger than what may be achieved with other materials. In Fig. 1 we show the dependence of the resistivity of an AlAs 2D electron system on stress, applied along the [100] direction, at a temperature of 0.3K. The sample is an 11nm-wide AlAs quantum well, grown on a GaAs (001) substrate, and bounded by $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ barriers that are modulation-doped with Si. It is patterned in the shape of a Hall bar aligned along the [100] crystal orientation. In order to apply stress, we used a newly-developed, simple technique, where we simply glue a thinned sample on the side of a stacked, piezoelectric actuator, with the [100] direction of the sample along the poling direction of the actuator. The technique allows us to apply *in-situ tunable* uniaxial stress, via changing the bias (V_P) applied to the piezo actuators, and measure the sample resistance. The resulting strain is calibrated with a metal-foil strain-gauge that is glued to the opposite side of the actuator; we define strain as $\epsilon = \epsilon_{[100]} - \epsilon_{[010]}$ where $\epsilon_{[100]}$ and $\epsilon_{[010]}$ are fractional length changes along the [100] and [010] directions, respectively.

We can understand the data of Fig. 1 qualitatively based on the occupation of the in-plane conduction band valleys, as schematically shown in Fig. 1. At zero strain, the valleys with their major axes along [100] and [100] directions (the X and Y valleys) are equally occupied. At lower values of piezo bias, as negative (compressive) stress is applied along the [100] direction, the energy of the X valley is lowered and there is a charge transfer from the Y to the X valley. For sufficiently large compressive strains, all the electrons are transferred to the X valley. Since for this valley, the electron effective mass for motion along [100] is larger than along [010], the resistivity along [100] also becomes larger. We emphasize that in this experiment, the density of 2D electrons, as monitored by measuring the Hall coefficient, does not change with applied stress.

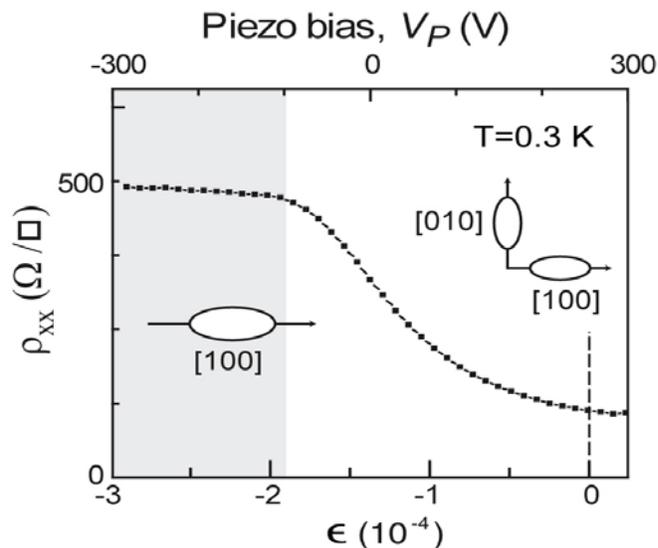


Fig. 1 Dependence of resistance along the [100] crystal direction (x-direction) on strain along the same direction, measured at a temperature of 0.3K in an AlAs 2D electron system. Here strain has negative values because the sample's length is diminished under compressive stress.

Of direct interest to this project is the change in resistivity observed as a function of strain (Fig. 1). Note that this change is more than a factor of two for a strain of $\sim 10^{-4}$. The maximum value of the (strain) gauge factor, defined as the fractional change of resistivity divided by the fractional change in sample length, is over 10,000. This is huge compared to conventional, metal-foil strain gauges that typically have a gauge factor of the order of 2, as dictated by the Poisson ratio. In the metal-foil case, the resistance change is primarily a result of geometric (size) change of the foil, while in the case of Fig. 1 data it is the basic electronic property (mobility along the current direction) that changes. It is worth emphasizing that piezoresistivity in multi-valley semiconductors has been known for decades, and was in fact used to disprove the single conduction band minimum model in bulk Si and Ge that was discussed in the early 1950s. Bulk Si and Ge themselves show large piezo-resistance effects and, in the case of lightly-doped Ge, the gauge factor can be as high as about 1,000 at liquid He temperature. 2D electrons in Si-MOSFETs, too, exhibit low-temperature piezoresistance gauge factors as large as about 50. The (001) AIAs 2D electrons, however, have a rather unique property. When confined to AIAs quantum wells of width larger than ~ 5 nm, the 2D electrons occupy only the two in-plane valleys. This means that with the application of in-plane uniaxial stress, one can *completely* depopulate one of the valleys and transfer all the electrons into the other valley. This results in the large piezoresistance effect observed in Fig. 1. Such a transfer is not possible in bulk Si or Ge, where multiple valleys are always occupied, or in Si-MOSFETs grown on (001) substrates where the 2D electrons occupy the two out-of-plane (*Z*) valleys and therefore the in-plane resistivity is isotropic and not a strong function of strain.

During the past few years, with the ARO support, we have characterized the piezoresistance effect in AIAs 2D electron systems. We measured the piezoresistance as a function of 2D electron density, valley occupation, magnetic field, and temperatures up to about 6K. We found that, as qualitatively expected, the piezoresistance is stronger at lower densities; this is because it takes smaller values of strain to transfer all the electrons from one valley to another. In the course of this work, we measured the “valley susceptibility” defined as the rate of valley polarization with applied strain. Note that this is analogous to the concept of “spin susceptibility,” which is defined as the rate of spin polarization with applied magnetic field. We made a surprising discovery: at lower densities the charge transfer (per unit strain) is enhanced compared to higher densities. The origin of this enhancement is the stronger electron-electron interaction [larger ratio of the Coulomb energy to the kinetic (i.e., Fermi) energy] at lower densities. (In a non-interacting picture, both the valley and spin susceptibilities should be constants, independent of 2D electron density). In our study we found that the enhancement of the valley susceptibility is indeed quantitatively very similar to the enhancement of the spin susceptibility observed in the same system. This remarkable observation establishes the *similarity of the valley and spin degrees of freedom*, with strain playing the role of magnetic field, and the valley energy splitting the role of the Zeeman energy splitting. The implication of this finding for the present project is that the low-temperature piezoresistivity of low-density AIAs 2D electrons is stronger than expected from the AIAs band parameters (namely, the band value of the effective mass and deformation potential).

We also measured the piezoresistance at higher temperatures, up to 6K. The results are encouraging as they indicate that the effect remains reasonably strong: The gauge factor drops only by a factor of about 2 or 3 from its value at 0.3K. This observation implies that AIAs 2D electrons can be used viably as a very sensitive strain sensor.

II.3. Piezoresistance of an AIAs 2D electron system patterned with an anti-dot lattice

The highlight of our work has been our discovery of an even stronger sensitivity to strain in AIAs 2D electron systems patterned with anti-dot lattices. Figure 2 summarizes the details and results of our piezoresistance experiments on AIAs 2D electrons patterned with anti-dot lattices. We first defined, via photo lithography, a Hall bar along the [100] direction (see upper right inset in Fig. 2). Then, via electron beam lithography and dry etching using an electron cyclotron resonance etcher we defined three anti-dot (AD) lattices with periods $a = 1, 0.8$ and $0.6 \mu\text{m}$ in three regions of the Hall bar, and left a fourth region un-patterned (blank) [see the upper insets of Fig. 2]. Each AD lattice is an array of holes (ADs) etched to a depth of 300 nm into the sample thus depleting the 2D electron system in the hole area (the 2D electrons are at a depth of about 100 nm from the top surface). The ratio d/a for each AD cell is about 1:3, where d is the AD diameter. We also deposited Ti/Au back- and front-gates to control the total 2D electron density (n) in the sample. In this experiment, at a piezo bias of V_p of -250 V, in the blank region the X and Y valleys are equally occupied (balanced) and, at $n = 3.8 \times 10^{11} \text{cm}^{-2}$ where the data of Fig. 3 were taken, electrons are all transferred to the Y valley for $V_p > 50\text{V}$ ($\epsilon > 1.5 \times 10^{-4}$); see the lower insets in Fig. 2.

The lower trace in Fig. 2 shows the piezoresistance in the blank region. This piezoresistance exhibits the anticipated behavior: the resistance drops with increasing strain as the electrons are transferred to the Y valley whose mobility is higher (because of its smaller effective mass) along the current direction. Beyond the valley depopulation point ($\epsilon > 1.5 \times 10^{-4}$), the resistance starts to saturate at a low value as the intervalley electron transfer ceases. This is the conventional piezoresistance effect in AIAs 2D electrons as described above. The dotted line in Fig. 2 in fact represents the best fit of the data to a simple model, which assumes that the valley populations change linearly with strain, and adds the conductivities of the two valleys to find the total conductivity; the model also assumes an isotropic scattering time for both valleys and ignores the inter-valley scattering.

The upper three traces in Fig. 2 represent the piezoresistance of the AD regions and demonstrate our main new finding. These traces exhibit an *increasing* resistance as a function of strain, opposite to the piezoresistance in the blank region. The strength of the piezoresistance effect is also quite prominent in the AD regions: indeed, in the $1 \mu\text{m}$ -AD region the resistance changes by about *ten* times for the range of applied strain while, in contrast, the change for the blank region is only about a factor of two. Furthermore, for all three AD regions, the piezoresistance persists beyond the valley depopulation point of the blank region ($\epsilon > 1.5 \times 10^{-4}$) where the blank region's piezoresistance nearly saturates.

These observations highlight the remarkable difference between the piezoresistance effect in the blank and the AD regions and present an interesting puzzle. We believe it is the presence of the AD lattice, which significantly modifies the strain distribution in the AIAs 2D electron system, that leads to the anomalous piezoresistance. To understand the strain distribution in the AD regions we performed a simple finite-element-method simulation (using FEMLAB) for a plane-strain problem of a 2D medium perforated with an array of holes. We apply a small tensile stress σ_x to the left and right sides, producing a small amount of strain ϵ_0 at x and $y \rightarrow \infty$; in other words, if there were no AD lattice, the strain would be uniform everywhere with a magnitude equal to ϵ_0 . The result of this simulation is shown in Fig. 3. There is clearly a non-uniform strain distribution due to the presence of the AD lattice. In particular, there are localized regions of enhanced strain (boxes A and B in Fig. 3), and of essentially zero strain (box C). For example, in

the upper and lower periphery of the AD (box A) the strain is enhanced by as much as $3\epsilon_0$. This enhancement by $3\epsilon_0$ is indeed indicated by an analytical solution of a 2D plane strain problem with a single hole. We add that our simulation of Fig. 3 is for a 2D system, however, we expect that in a system which contains an AD lattice at its top surface, the strain profile is qualitatively similar to what is shown in Fig. 3.

But how does a non-uniform strain distribution lead to an increase in resistance? Note that, in our experiment, positive (negative) strain leads to a valley splitting that favors the Y valley (X valley) occupation. This means that electrons occupying either the X or Y valley feel an extra, modulated, and confining potential (besides being excluded from the AD hole regions) as they move through the AD lattice. We believe that it is this potential that profoundly affects the quasi-ballistic motion of electrons in the AD region and leads to the observed piezoresistance. For example, consider the localized enhancement of positive strain in box A of Fig. 3. Such strain depletes the X -valley electrons in box A and effectively narrows the width of the channels (between the AD holes) through which they have to travel to carry current to the right.

Our additional magneto-transport measurements and numerical simulations lend further support to this picture. For example, they show the appearance of sub-harmonic commensurability oscillation peaks in the magneto-resistance, strongly suggesting a "channel-pinching effect" in the strained AD lattice for the X -valley electrons. As shown schematically in Fig. 4, the X -valley electrons are excluded from the regions near the edges of the ADs (in the

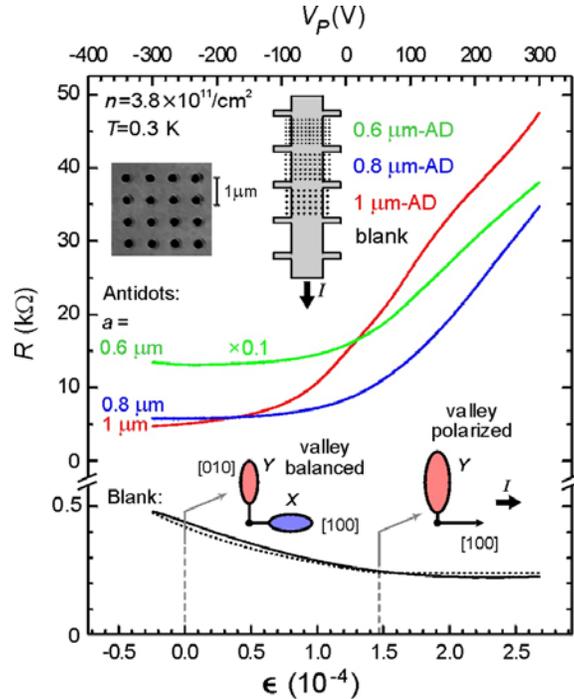


Fig. 2 The piezoresistance of an AlAs 2D electron system in the un-patterned (blank) region (lower trace) and in three anti-dot (AD) regions (upper three traces). The dotted line is the best fit to the piezoresistance in the blank region based on a conventional model. Upper insets: A micrograph of an AD lattice (with period $a = 0.8 \mu\text{m}$) and sections of the Hall bar. Lower insets: The orientation and occupation of the valleys are schematically shown for the blank region at $\epsilon = 0$ where the two valleys are equally occupied and for $\epsilon > 1.5 \times 10^{-4}$ where all the electrons are transferred to the Y valley.

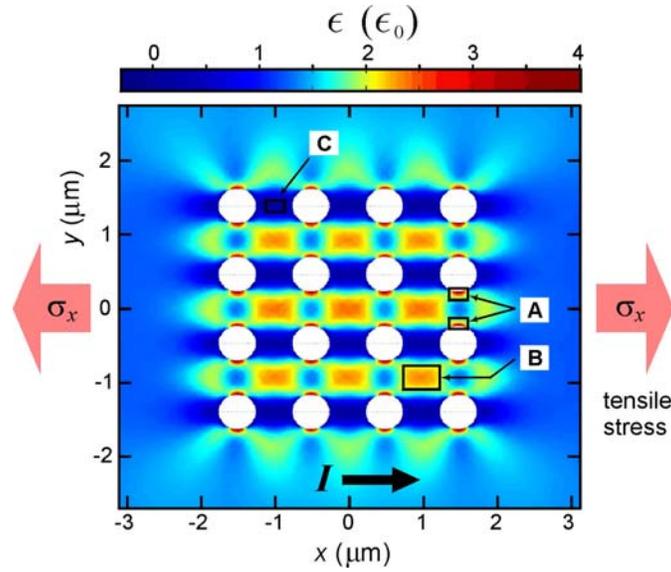


Fig. 3 (Color) Finite element simulation of the strain distribution in a 2D medium perforated with an AD lattice. Boxes A and B highlight the areas of enhanced strain; box C highlights a region of reduced strain.

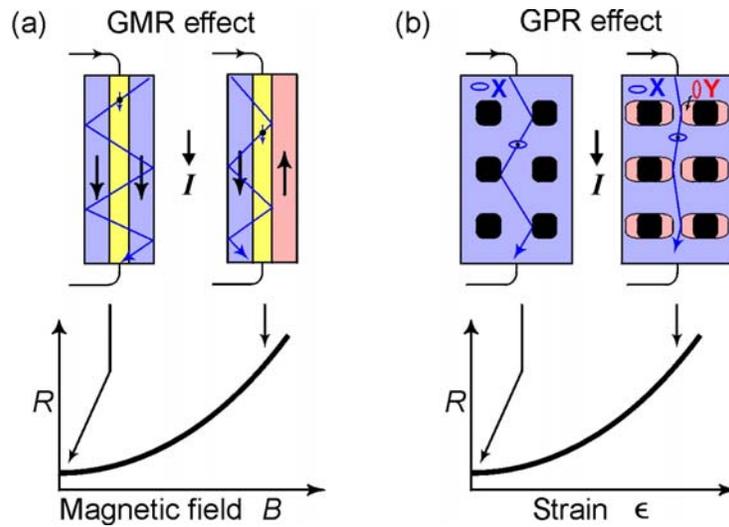


Fig. 4 (Color) Comparison between: (a) the GMR (giant magnetoresistance) effect in a layered magnetic metal sandwich structure and (b) the GPR (giant piezoresistance) effect in AIs 2DES with an AD lattice.

direction perpendicular to the current direction) so that these electrons would have to go through much narrower channels. The result is an enhancement of the resistance as observed in the experiments and also indicated in the numerical resistance simulations. This channel-pinching picture suggests a remarkable resemblance between our “giant piezo-resistance” (GPR) effect and the “giant magneto-resistance” (GMR) effect, observed in thin-film structures composed of alternating layers of ferromagnetic and non-magnetic materials. A comparison of these two effects is schematically illustrated in Fig. 4. In each structure, the reversal of polarization of the magnetization (spin) or valley in the regions adjacent to the active channel due to either external magnetic field (B) or applied strain (ϵ) leads to a narrower effective channel width (extra confinement) for the X -valley electrons, and additional scattering for both X and Y -valley electrons (because of the modulated potential); both of these effects lead to higher resistance.

Regardless of its origin, the GPR exhibited by our AD lattices reveals the extreme sensitivity of their resistance to strain. The data of the $1\ \mu\text{m}$ AD lattice, e.g., yield a maximum strain gauge factor of over 20,000. This is a factor of two larger than the largest gauge factor we have observed in any of our un-patterned AlAs 2D electron systems. In fact, using a simple resistance measurement, we were able to detect strains down to 1×10^{-8} with our AD samples. Given that the spacing between our Hall bar resistance contacts is $40\ \mu\text{m}$, this strain translates to a displacement of $4 \times 10^{-4}\ \text{nm}$ (about 1/100 of the Bohr radius)!

II.4. Piezoresistance of GaAs 2D holes

We recently measured the piezoresistance of 2D *hole* systems confined to GaAs quantum wells and GaAs/AlGaAs heterojunctions grown on GaAs (311)A substrates. Examples of such data are shown in Fig. 5. Three aspects of the data are noteworthy. First, the observed piezoresistance is very anisotropic, with the $[011\bar{1}]$ direction exhibiting a much larger change in resistance with strain than the $[2\bar{1}33]$ direction. Second, the piezoresistance is nearly linear with strain. Third, there is a strong dependence of the piezoresistance on the 2D hole density, with the largest effect seen at the lowest densities.

It turns out that the origin of the piezoresistance in the 2D hole system is very different from that of 2D electrons in AlAs. In the 2D hole case, it is the deformation of the Fermi contour with strain that leads to piezoresistance. This is illustrated in Fig. 6 where we show plots of the calculated Fermi contours for the spin-orbit interaction induced spin-split heavy and light heavy-hole (HHh and HHL) bands at different values of strain. Note in particular that the HHh band, which contains the majority of holes, becomes severely anisotropic with the application of strain. For a positive value of strain, e.g., the HHh band is much more elongated along $[011\bar{1}]$, implying a larger effective mass along this direction. This larger mass in turn means a larger resistance along $[011\bar{1}]$, qualitatively consistent with the experimental data of Fig. 5. We note, however, that a simple calculation of the piezoresistance does not agree quantitatively with the measurements: the calculations underestimate the piezoresistance along the $[011\bar{1}]$ but overestimate it along the $[2\bar{1}33]$. In other words, they do not explain the extreme anisotropy that is experimentally observed. The origin of this discrepancy and, in particular, the very large piezoresistance anisotropy observed in the experiments is unclear at the moment.

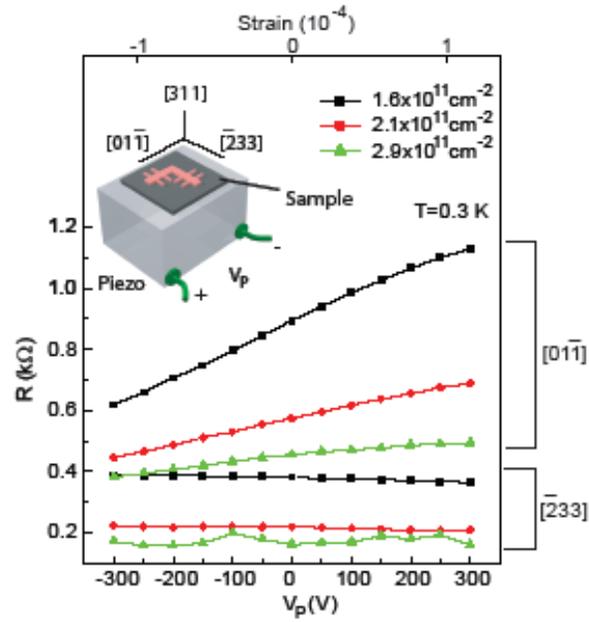


Fig. 5 Piezoresistance of a GaAs 2D hole system in a GaAs/AlGaAs heterojunction measured along the $[011\bar{1}]$ and $[2\bar{3}3]$ directions for three different densities. Inset: Experimental setup.

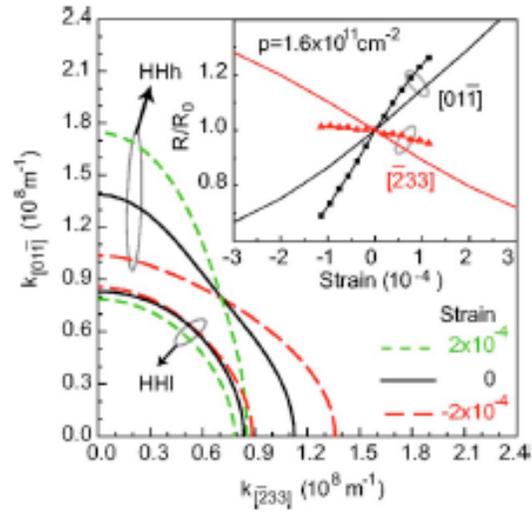


Fig. 6 Calculated Fermi contours for the Hhh and HHI spin subbands; $k_{[011\bar{1}]}$ and $k_{[2\bar{3}3]}$ are the wavevectors along the two perpendicular ($[011\bar{1}]$ and $[2\bar{3}3]$) directions. Inset: Comparison between the experimental (symbols) and calculated (lines) piezoresistances.

III. Publications acknowledging ARO support

We list here 2004-2007 publications which have been partially supported by and have acknowledged ARO support. Note that some of these publications have resulted from work supported by the PI's earlier ARO grants.

1. O. Gunawan, Y.P. Shkolnikov, E.P. De Poortere, E. Tutuc, and M. Shayegan, "Ballistic Transport in AlAs Two-dimensional Electrons," *Phys. Rev. Lett.* **93**, 246603 (2004).
2. E.P. De Poortere and M. Shayegan, "A Hybrid $\text{Al}_{0.10}\text{Ga}_{0.90}\text{As}/\text{AlAs}$ Bilayer Electron System," *Appl. Phys. Lett.* **84**, 3837 (2004).
3. Y.P. Shkolnikov, K. Vakili, E.P. DePoortere, and M. Shayegan, "Giant Low-temperature Piezoresistance Effect in AlAs Two-dimensional Electrons," *Appl. Phys. Lett.* **85**, 3766 (2004).
4. B. Habib, E. Tutuc, S. Melinte, M. Shayegan, D. Wasserman, S.A. Lyon, and R. Winkler, "Negative Differential Rashba Effect in Two-dimensional Hole Systems," *Appl. Phys. Lett.* **85**, 3151 (2004).
5. B. Habib, E. Tutuc, S. Melinte, M. Shayegan, D. Wasserman, S.A. Lyon, and R. Winkler "Spin Splitting in GaAs (100) Two-dimensional Holes," *Phys. Rev. B* **69**, 113311 (2004).
6. C. Gustin, S. Faniel, B. Hackens, S. Melinte, M. Shayegan, and V. Bayot, "Orbital Effect, Subband Depopulation, and Conductance Fluctuations in Ballistic Quantum Dots under a Tilted Magnetic Field," *Phys. Rev. B* **71**, 155314 (2005).
7. E. Tutuc and M. Shayegan, "Interaction and Disorder in Bilayer Counterflow Transport at Filling Factor One," *Phys. Rev. B* **72** (Rapid Communications), 081307 (2005).
8. R. Winkler, E. Tutuc, S.J. Papadakis, S. Melinte, M. Shayegan, D. Wasserman, and S.A. Lyon, "Anomalous Spin Polarization of GaAs Two-dimensional Hole Systems," *Phys. Rev. B* **72**, 195321 (2005).
9. Y.P. Shkolnikov, S. Misra, N.C. Bishop, E.P. De Poortere, and M. Shayegan, "Observation of Quantum Hall Valley Skyrmions," *Phys. Rev. Lett.* **95**, 066809 (2005).
10. K. Vakili, Y.P. Shkolnikov, E. Tutuc, E.P. De Poortere, M. Padmanabhan, and M. Shayegan, "High-mobility Out-of-plane Valley Occupation in AlAs Quantum Wells," *Appl. Phys. Lett.* **89**, 172118 (2006).
11. M. Shayegan, E.P. De Poortere, O. Gunawan, Y.P. Shkolnikov, E. Tutuc, and K. Vakili, "Two-dimensional Electrons Occupying Multiple Valleys in AlAs," (review article), *Phys. Stat. Sol. (b)* **243**, 3629-3642 (2006).
12. O. Gunawan, Y.P. Shkolnikov, K. Vakili, T. Gokmen, E.P. De Poortere, and M. Shayegan, "Valley Susceptibility of an Interacting Two-dimensional Electron System," *Phys. Rev. Lett.* **97**, 186404 (2006).
13. O. Gunawan, B. Habib, E.P. De Poortere, and M. Shayegan, "Quantized Conductance in an AlAs 2D Electron System Quantum Point Contact," *Phys. Rev. B* **74**, 155436 (2006).
14. O. Gunawan, T. Gokmen, K. Vakili, M. Padmanabhan, E.P. De Poortere, and M. Shayegan, "Spin-valley Phase Diagram of the Two-dimensional Metal-insulator

Transition,” *Nature Physics* **3**, 388-391 (2007). See commentary (“News and Views”) by Jurgen H. Smet, “Metal-insulator Transition: A Plane Mystery,” *Nature Physics* **3**, 370-372 (2007).

15. O. Gunawan, E.P. De Poortere, and M. Shayegan, “AlAs 2D Electrons in an Antidot Lattice: Electron Pinball with Elliptical Fermi Contours,” *Phys. Rev. B* **75**, 081304 (2007).
16. B. Habib, J. Shabani, E.P. De Poortere, M. Shayegan, and R. Winkler, “Tuning of the Spin-orbit Interaction in Two-dimensional GaAs Holes via Strain,” *Phys. Rev. B* **75**, 153304 (2007).
17. B. Habib, J. Shabani, E.P. De Poortere, M. Shayegan, and R. Winkler, “Anisotropic Low-temperature Piezoresistance in (311)A GaAs Two-dimensional Holes,” *Appl. Phys. Lett.* **91**, 012107 (2007).
18. O. Gunawan, T. Gokmen, Y.P. Shkolnikov, E.P. De Poortere, and M. Shayegan, “Anomalous Giant Piezoresistance in AlAs Two-dimensional Electrons with Antidot Lattices,” *Phys. Rev. Lett.* **100**, 036602 (2008).
19. J. Shabani, M. Shayegan, and R. Winkler, “Strain-induced Fermi Contour Anisotropy of GaAs Two-dimensional Holes,” *Phys. Rev. Lett.* **100**, xxxxxx (2008).
20. O. Gunawan, T. Gokmen, E.P. De Poortere, and M. Shayegan, “Characterization of the Anomalous Giant Piezoresistance in AlAs Two-dimensional Electrons with Antidot Lattices,” submitted for publication.

IV. Educational Component

The projects were performed primarily by graduate students and were crucial for their education and training. The PI is dedicated to the education of both graduate and undergraduate students and works with them closely in the lab. He believes that doing state-of-the-art research, with close supervision, is the best way to learn beyond textbooks and homework sets. High quality education was therefore integrated into the research that is described here. Also, both the fabrication and the physics of advanced, low-dimensional semiconductor structures are at the forefront of today’s science and technology; well-trained and educated students in this field are invaluable resources for the US as well as the rest of the world.