Effects of biased and unbiased illuminations on dopant-free GaAs/AlGaAs 2DEGs

A. Shetty, 1, 2 F. Sfigakis, 1, 2, 3, 4, * W. Y. Mak, 3 K. Das Gupta, 5
B. Buonacorsi, 1, 6 M. C. Tam, 7 H. S. Kim, 7 I. Farrer, 3, 8 A. F. Croxall, 3 H. E. Beere, 3
A. R. Hamilton, 9 M. Pepper, 10 D. G. Austing, 11 S. A. Studenikin, 11 A. Sachrajda, 11
M. E. Reimer, 1, 4, 6, 7 Z. R. Wasilewski, 1, 4, 6, 7, 12 D. A. Ritchie, 3 and J. Baugh†, 1, 2, 4, 6, 12, *

1 Institute for Quantum Computing, University of Waterloo, Waterloo N2L 3G1, Canada
2 Department of Chemistry, University of Waterloo, Waterloo N2L 3G1, Canada
3 Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
4 Northern Quantum Lights Inc., Waterloo N2B 1N5, Canada
5 Department of Physics, Indian Institute of Technology Bombay, Mumbai 40007, India
6 Department of Physics and Astronomy, University of Waterloo, Waterloo N2L 3G1, Canada
7 Department of Electrical and Computer Engineering, University of Waterloo, Waterloo N2L 3G1, Canada
8 Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, UK
9 School of Physics, University of New South Wales, Sydney NSW 2052, Australia
10 School of Physics, University of New South Wales, Sydney NSW 2052, Australia
11 Security and Disruptive Technologies Research Centre, National Research Council of Canada, Ottawa, K1A 0R6, Canada
12 Waterloo Institute for Nanotechnology, University of Waterloo, Waterloo N2L 3G1, Canada

* corresponding author: francois.sfigakis@uwaterloo.ca
† baugh@uwaterloo.ca

I. INTRODUCTION

Illumination is a well-known technique for increasing the mobility of two-dimensional electron gases (2DEGs) in modulation-doped GaAs/AlGaAs heterostructures at cryogenic temperatures. This effect, known as persistent photoconductivity [1–3], can last for many weeks, as long as the sample is not warmed up above temperature \( T \sim 100 \text{ K} \). In many cases, mobility is increased primarily through the increase of the electron density, which makes more effective Thomas-Fermi screening of charged impurities. The increase in carrier density is mostly achieved by exciting electrons out of deep-level donor impurity complexes known as DX centers [4–7]. The photo-excited electrons are captured in the GaAs conducting channel. Incremental illumination in small doses (intensity \( \times \) duration) can be used for precise tuning of the carrier concentration in modulation-doped ungated heterostructures [8]. Aside from acting on DX centers, illumination may also have other effects, such as activating or deactivating unintentional impurity atoms in the transport channel itself. In modulation-doped 2DEGs, this can be difficult to separate from effects associated with the intentional dopants, which typically outnumber background impurities by three to five orders of magnitude.

The limitation described above can be circumvented by using GaAs-based dopant-free field effect transistors (FET), either in the semiconductor-insulator-semiconductor field effect transistor (SISFET) geometry [9–15] or the heterostructure-insulator-gate field effect transistor (HIGFET) geometry [16–24]. Dopant-free field effect transistors have been used to produce quantum wires [16, 25–27] and quantum dots [28–32]. Relative to their modulation-doped counterparts, dopant-free devices have exceptional reproducibility and low disorder [27, 30, 33], potentially making them suitable to study fragile fractional quantum Hall states [19, 24]. Illumination has been studied in SISFETs, but with conflicting reports [10, 13, 34]. The effect had not been studied in HIGFETs [35], until very recently [36].

Understanding the effects of biased illumination is particularly relevant for the recently active field of photon spin devices in quantum optoelectronics. Such devices, with possible applications such as spin-to-photon [37] or photon-to-spin [38] conversions, often need to be peri-
FIG. 1. (color online) MBE layer structure of GaAs/AlGaAs single heterojunctions used in: (a) Series I, and (b) Series II. Table I lists the AlGaAs barrier thickness for each wafer. The dashed red line indicates the location of the 2DEG.

This issue is also relevant for some proposed single photon source proposals [39, 40] which would use so-called “lateral” dopant-free p-i-n junctions [41–43].

In this article, we report on the effects of illumination on 2DEGs in dopant-free Hall bars in the HIGFET geometry, with the 2DEG depth below the surface ranging from 30 nm to 310 nm. We model the mobility, and quantify the effects of illumination on surface states and background impurities. We characterize biased illumination, an experimental technique where illumination is performed while gates are held at finite voltages, whose effects are markedly different from unbiased illumination. Biased illumination appears to allow in-situ control of surface charge. Section II covers the growth and fabrication of samples, section III covers the scattering theory used to model mobilities, section IV covers the transport experiments, and section V covers the discussion and conclusions about the work presented here.

TABLE I. Index of samples for which data is shown in at least one figure of the main text (20 devices in total were measured). The MBE layer structure of the wafers is shown in Figure 1.

| Sample ID | Wafer ID | 2DEG depth (nm) | AlGaAs barrier (nm) |
|-----------|---------|----------------|---------------------|
| Series I  |         |                |                     |
| A         | W639    | 160            | 150                 |
| B         | W640    | 110            | 100                 |
| C         | W641    | 60             | 50                  |
| D         | V627    | 30             | 20                  |
| Series II |         |                |                     |
| E         | G404    | 310            | 300                 |
| F         | G404    | 310            | 300                 |
| G         | G404    | 310            | 300                 |
| H         | G373    | 160            | 150                 |
| J         | G372    | 110            | 100                 |
| K         | G370    | 75             | 65                  |
| L         | G370    | 75             | 65                  |
| M         | G370    | 75             | 65                  |

II. SAMPLE GROWTH AND FABRICATION

Two series of dopant-free GaAs/AlGaAs heterostructures [44], each with varying single-heterojunction depths, were grown by molecular beam epitaxy (MBE). Series I included three GaAs/Al$_{0.33}$Ga$_{0.67}$As structures (W639, W640, and W641) grown on the same day, and an ultra-shallow heterojunction (V627) grown in a different chamber with an Al$_{0.95}$Ga$_{0.05}$As barrier. Series II, grown later in a third chamber, included three GaAs/Al$_{0.30}$Ga$_{0.70}$As heterojunctions (G370, G372, and G373) grown over two consecutive days, as well as a much deeper heterojunction (G404) grown several weeks later. The MBE layer structures of the two series are shown in Figure 1. The AlGaAs barrier layer thickness was varied from 20 nm to 300 nm, and is listed in Table I for each wafer. All wafers were grown on 3” semi-insulating (SI) GaAs (001) substrates.

Hall bars were fabricated on all 8 wafers, and oriented in the high mobility crystal direction [110]. All devices from Series I wafers were unipolar Hall bars (2DEG only). All devices from Series II wafers (except where specified) were ambipolar Hall bars, with both n-type and p-type ohmic contacts. This allowed a two-dimensional electron gas (2DEG) or a two-dimensional hole gas (2DHG) to be induced, depending on the voltage polarity applied to the topgate.

The fabrication of unipolar (2DEG only) Hall bars on wafers from Series I is extensively described in Ref. [18]. Briefly, after deposition and anneal of the recessed Ni/AuGe/Ni n-type ohmic contacts, a 500 nm insulator layer of photoimageable polyimide (HD4104) was spin-coated and cured at 250°C, with typical breakdown voltages of 25–35 Volts [see Fig. 1(c) in Ref. 30]. Above the insulator layer, a thin Ti/Au (5 nm/1 nm) semi-transparent topgate covers the entire surface of the 2DEG (overlapping the ohmic contacts), and varies the electron density. Surprisingly, otherwise identical Hall bars with a thicker, “opaque” topgate (Ti/Au 20/80 nm) gave similar results as those presented here with the thin topgates. Because of the thick polyimide insulator layer, we speculate that light can travel inwards and underneath the topgate from its edges.

The fabrication of ambipolar Hall bars on wafers from
III. BOLTZMANN TRANSPORT MODEL

The mobility \( \mu \) of carriers (electrons or holes) is limited by their interactions with their environment via scattering events, and relates to the momentum relaxation time \( \tau \) (also known as the transport scattering time) by \( \mu = e\tau/m^* \), where \( m^* \) is the effective mass and \( e \) the elementary charge. The total scattering rate \( 1/\tau_{\text{total}} \) of carriers is simply the sum of the rates of all scattering mechanisms occurring in the system, \( 1/\tau_{\text{total}} = \sum_i 1/\tau_i \) (Matthiessen’s rule [45]). Thus, we model the mobility as [46]:

\[
\frac{1}{\mu} = m^* \left( \frac{1}{\tau_{\text{m}-1}} + \frac{1}{\tau_{\text{m}-2}} + \frac{1}{\tau_{\text{m}}} + \frac{1}{\tau_{\text{sc}}} \right) \quad (1)
\]

where \( 1/\tau_{\text{m}-1} \) is the scattering rate due to ionized background impurities in AlGaAs, \( 1/\tau_{\text{m}-2} \) is the scattering rate due to ionized background impurities in GaAs, \( 1/\tau_{\text{m}} \) is the scattering rate due to the GaAs/AlGaAs interface roughness, and \( 1/\tau_{\text{sc}} \) is the scattering rate due to surface charges. Phonon scattering is neglected, as all measurements were performed at the same low temperature (T \( \sim 1.5 \) K) and are only compared relative to each other. Sources of scattering are treated within the semi-classical Boltzmann transport formalism. A detailed derivation of how each scattering mechanism contributes to the mobility can be found elsewhere [47-49], but some of the key approximations and expressions are described below and in the Appendix.

Electrons are described by the Fang-Howard wavefunction \( \Psi(\mathbf{r}, z) \propto \psi(z) e^{ik \cdot \mathbf{r}} \), where \( \mathbf{r} \) is any direction within the \( x-y \) (2DEG) plane and \( z \) is the MBE growth direction. The 2DEG resides at the GaAs/AlGaAs interface at \( z = 0 \) [Fig. 3]. Following the orientation convention in Fig. 3, the wavefunction \( \psi(z) \) is [50, 51]:

\[
\psi(z) = \begin{cases} 
0 & \text{for } z < 0 \\
\left( \frac{b^3 z^2}{2} \right)^{1/2} e^{-bz/2} & \text{for } z \geq 0 
\end{cases} \quad (2)
\]

with \( b = \left( \frac{33m_z \epsilon^2 n_{2D}}{8\hbar^2 \epsilon_0 \epsilon_r} \right)^{1/3} \) (3)

where \( m_z \) is the effective mass in the growth direction \( (m_z = m^* = 0.067m_0 \) for electrons with \( m_0 \) the free electron mass), \( \epsilon_0 \) the vacuum permittivity, \( \epsilon_r \) the relative permittivity of GaAs and AlGaAs (approximating \( \epsilon_r = \epsilon_{\text{GaAs}}^r \approx \epsilon_{\text{AlGaAs}}^r \approx 12.8 \)), and \( n_{2D} \) the 2D carrier sheet density. The \( \psi(z) \) wavefunction typically spans 10-30 nm at the carrier densities used in experiments, and its maximum occurs at a distance of \( 2/b \) below the GaAs/AlGaAs interface. The Fang-Howard wavefunction leads to the following form factor \( F_{\psi}(q) \):

\[
F_{\psi}(q) = \int_0^\infty \int_0^\infty |\psi(z)|^2 |\psi(z')|^2 e^{-q|z-z'|} \, dz \, dz' \quad (5)
\]

\[
F_{\psi}(q) = \frac{2}{8} \left( \frac{b}{b+q} \right)^3 + 3 \left( \frac{b}{b+q} \right)^2 + 3 \left( \frac{b}{b+q} \right) \quad (6)
\]

where \( q = 2k_F \sin(\theta/2) \) is the scattering wavevector (with scattering angle \( \theta \)) and \( k_F = \sqrt{2\pi n_{2D}} \) is the Fermi wavevector.

Taking into account that the potential from an ionized impurity is partially screened by the 2DEG (dielectric screening) and using the Thomas-Fermi approximation, the dielectric function \( \epsilon(q) \) can be written as:

\[
\epsilon(q) = 1 + \frac{\epsilon^2}{2\epsilon_0 \epsilon_r \hbar^2} F_{\psi}(q) \quad (7)
\]

which includes \( F_{\psi}(q) \) to account for the finite width of the 2DEG wavefunction.

Applying Fermi’s golden rule to a 2DEG with scattering potential \( U(q) \), the following general expression for...
the scattering rate at temperature \( T = 0 \) is obtained [49, 52]:

\[
\frac{1}{\tau} = \frac{m^*}{\pi \hbar^3 k_F^2} \int_0^{2k_F} \frac{|U(q)|^2}{\epsilon(q)^2} \frac{q^2}{\sqrt{4k_F^2 - q^2}} dq
\]

(8)

for which the corresponding \(|U(q)|^2\) terms and associated scattering rates \( 1/\tau_{\text{ir}}\), \( 1/\tau_{\text{sc}}\), \( 1/\tau_{\text{bi-1}}\), and \( 1/\tau_{\text{bi-2}}\) are described respectively by equations (A2), (B4), (C4), and (D7) in the Appendix. For convenience, only the final expressions for the scattering rate of each mechanism are listed below:

\[
\frac{1}{\tau_{\text{ir}}} = \frac{(\Delta \Delta)^2 m^*}{2\hbar^3 k_F^2} \left( \frac{n_2d}{2\epsilon_0 \epsilon_r} \right)^2 \frac{e^2}{\epsilon(q)^2} \int_0^{\pi} \frac{q^2 e^{-q^2/4}}{\epsilon(q)^2} d\theta
\]

(9)

\[
\frac{1}{\tau_{\text{sc}}} = \frac{N_{\text{sc}} m^*}{2\pi \hbar^3 k_F^2} \left( \frac{e^2}{2\epsilon_0 \epsilon_r} \right)^2 \int_0^{\pi} \frac{e^{-2qd}}{\epsilon(q)^2 (1 + q/b)^6} d\theta
\]

(10)

\[
\frac{1}{\tau_{\text{bi-1}}} = \frac{N_{\text{bi-1}} m^*}{2\pi \hbar^3 k_F^2} \left( \frac{e^2}{2\epsilon_0 \epsilon_r} \right)^2 \int_0^{\pi} \frac{\epsilon(q)^2}{(1 + q/b)^6} d\theta
\]

(11)

\[
\frac{1}{\tau_{\text{bi-2}}} = \frac{N_{\text{bi-2}} m^*}{2\pi \hbar^3 k_F^2} \left( \frac{e^2}{2\epsilon_0 \epsilon_r} \right)^2 \int_0^{\pi} \frac{F_{\text{GaAs}}(q)}{\epsilon(q)^2} d\theta
\]

(12)

where \( \Delta \) is the height of irregularities in the \( z \) direction at the GaAs/AIGaAs interface (Fig. 3), \( \Delta \) is the separation distance in the \( x-y \) plane between these irregularities [Fig. 3], \( d \) is the distance of the GaAs/AIGaAs interface (or nominal 2DEG depth) to the wafer surface, \( N_{\text{sc}} \) is the sheet concentration of surface charges, \( N_{\text{bi-1}} \) is the volume concentration of background impurities in AIGaAs, \( N_{\text{bi-2}} \) is the volume concentration of background impurities in GaAs, and \( F_{\text{GaAs}}(q) \) is a form factor described by equation (D5). By substituting the scattering rates \( 1/\tau_i \) expressed in eqns. (9)–(12) into equation (1), the transport mobility can be calculated.

This model has been very successful at describing behavior both from shallow and deep dopant-free 2DEGs [see Ref. 18, as well as Figures 12 and 13 in the Appendix]. The model’s implementation in code is available online [53]. Since we experimentally extract the interface roughness parameters \( \Delta \) and \( \Delta \) from wafer surface analysis with an atomic force microscope (AFM), these parameters are not unrestricted free variables when fitting experimental mobilities to this model. In the case of deep 2DEGs (where \( N_{\text{sc}} \) is negligible), curve-fitting can be reduced to a single free variable: the average background impurity concentration \( N_{\text{bi}} = N_{\text{bi-1}} = N_{\text{bi-2}} \) [see Figure 13 in the Appendix].

IV. EXPERIMENTS AND ANALYSIS

The following applies to all Hall bar measurements described here. Constant current (100 nA) four-terminal measurements were performed in two pumped-\(^{4}\)He cryostats (\( T \sim 1.5 \) K), with standard AC lock-in techniques using SR-830 lock-ins and SR-560 voltage preamplifiers [54]. Typical ohmic contact resistances were 500-1500 \( \Omega \) in 2DEGs (these are resistive because of the thick 120 nm Ni capping layer) and less than 200 \( \Omega \) in 2DHGs. There was no measurable leakage current from the topgate to the 2DEG above the \( \sim 10 \) pA noise floor of the DC measurement setup, for any topgate voltage applied. Mobility and carrier density were obtained from the following relations:

\[
n_{2D} = \frac{IB}{e \nu_{2D}}
\]

(13)

\[
\mu = \frac{I(L/W)}{e2n_{2D}v_{xx}}
\]

(14)

where \( n_{2D} \) is the Hall electron carrier density, \( I \) is the ac excitation current (along the \( x \) direction), \( B \) is the magnetic field (oriented perpendicular to the 2DEG plane), \( V_{\text{HH}} \) is the Hall voltage (obtained from \( V_{\text{HH}} = |V_{xy}(B) - V_{xy}(-B)|/2 \), which eliminates any offsets in \( V_{xy} \) at \( B=0 \), \( W \) is the width of the Hall bar (corresponding to the edges of the topgate), \( L \) is the (center-to-center) distance between voltage probe contacts on the Hall bar, and \( V_{xx} \) is the voltage drop along the direction of the ac current \( I \) in the high-mobility crystal direction [110]. Data for carrier density and mobilities was taken with four significant digits and uncertainty ranging from \( \pm 0.05\% \) to \( \pm 3\% \). Error bars in plots are thus smaller than the marker symbols used, and are not shown. All data shown in Figures 4–6 and 9–11 have been reproduced in at least two Hall bars, unless noted otherwise.

Experimental results are presented in two parts: unbiased illumination in section IV A, and biased illumination in section IV B.

A. Unbiased illumination, while \( V_{\text{topgate}} = 0 \)

Examples of reproducibility prior to illumination are shown in Figure 4(a), showing mobility measurements from two separate cooldowns on the same Hall bar, and in Figure 4(b), showing mobility measurements on two separate Hall bars from the same wafer. The narrow Shubnikov-de-Haas (SdH) oscillations and quantum Hall (QH) effect observed in Figure 4(c) are consistent with high mobilities. The minima of SdH oscillations reach \( R_{xx} = 0 \); there is no parallel conduction. The carrier density extracted from the SdH oscillations matches that of the Hall density; the 2DEG occupies a single subband.

For all Hall bars from both Series I (polymide insulator) and Series II (SiO\(_2\) insulator), the \( n_{2D}(V_{\text{topgate}}) \) relationships shown in Figures 5(a) and 5(b) are linear and non-hysteretic, confirming no significant gate leakage or re-chargeable traps in the insulator. Before illumination, the topgate voltage in samples from Series II was limited to \( |V_{\text{topgate}}| < 5 \) V to prevent gate hysteresis (this is discussed further in section IV B). Series I samples were illuminated directly with a red LED driven at 10 mA. Series II samples were illuminated indirectly with another red LED driven at 78 mA. Illumination ranged in durations from 5 seconds to 8 minutes, while samples
FIG. 4. (color online) (a) Reproducibility of mobility between two cooldowns of the same Hall bar, before illumination. (b) Reproducibility of mobility characteristics for two Hall bars from the same wafer before illumination. (c) Typical quantum Hall effect and Shubnikov-de-Haas oscillations before illumination, with visible quantized Hall plateaus at filling factors $\nu = 2, 3, 4, 6, \text{and } 8$.

were grounded and no voltage was applied to the topgate (unbiased illumination). The largest change occurs during the first 5 seconds of illumination for Series II samples, and subsequent illuminations have a smaller effect. A typical example for the density-topgate relation $n_{2D}(V_{\text{topgate}})$ is shown in Figure 5(c), before and after illuminations of varying durations.

Two observations can be drawn from Figures 5(a) and 5(b). First, the slope of the density-voltage relation, a direct measurement of the capacitance between the 2DEG and the topgate, does not change before/after illumination within $1\text{-}2\%$. Second, it becomes more difficult to induce electrons in the GaAs channel after illumination, irrespective of insulator type or MBE growth chamber, requiring significantly higher 2DEG turn-on threshold topgate voltages $V_{\text{th}}$, defined as the extrapolated $n_{2D} = 0$ intercept on the topgate voltage axis [55]. This is contrary to what was observed in previous studies of illumination on 2DEGs in SISFETs [10, 13, 34], where $V_{\text{th}}$ was lower to achieve the same electron density after illumination. However, in SISFETs, the gate used to induce a 2DEG is a degenerately-doped GaAs cap layer, which completely screens surface states and prevents them from affecting $V_{\text{th}}$. With metal gates in dopant-free HIGFETs, such screening does not occur. Charged traps inside or at the interface between the amorphous gate dielectric (SiO$_2$ or polyimide) and the GaAs cap layer can affect $V_{\text{th}}$, as well as any surface treatment immediately prior to gate dielectric deposition [36].

A typical example of the mobility-density relation $\mu(n_{2D})$ is shown in Figure 5(d) at $T = 1.4 \text{ K}$, before and after illuminations of varying durations. After illumination, electron mobility is improved. Most of the change occurs during the first 5 seconds of illumination, with eventual saturation at longer illumination times.

FIG. 5. (color online) Electron density versus topgate voltage relationships $n_{2D}(V_{\text{topgate}})$, before (black squares) and after (red circles) illumination, typical of Hall bars from all wafers fabricated with a: (a) polyimide insulator, and (b) SiO$_2$ insulator. (c) In all wafers, after the initial 5 seconds, longer illuminations did not appear to cause further change in $n_{2D}(V_{\text{topgate}})$. (d) After illumination, electron mobility improves. Most of the change occurs during the first 5 seconds of illumination, with eventual saturation at longer illumination times.

Figure 6 shows experimental electron mobilities as a function of electron density for wafers from Series I and Series II, before and after illumination to saturation. As expected, within a wafer series, mobility decreases as the 2DEG becomes closer to the surface [56], in line with previous studies, both in dopant-free 2DEGs and modulation-doped 2DEGs [18, 30]. Scattering from surface charges is the primary mechanism for this mobility degradation, and becomes pronounced for 2DEG depths smaller than $\sim 80 \text{ nm}$ [13, 18, 57]. This is also shown experimentally and theoretically in Fig. 12 in Appendix B. In Figure 6, illumination increases the electron mobility by up to $30\%$ for the six deepest 2DEGs, where the surface is $75 \text{ nm}$ or more away. For the two shallowest 2DEGs (Figs. 6(c) and 6(d), $60 \text{ nm}$ and $30 \text{ nm}$ deep, respectively), mobility decreases after illumination. This decrease in only the two shallowest of the eight 2DEGs surveyed strongly suggests that surface charge plays a role. Previous studies on SISFETs used 2DEGs deep
FIG. 6. (color online) Electron mobilities before (black squares) and after (red circles) illumination for: (a)–(d) Series I wafers and (e)–(h) Series II wafers. Series I (Series II) wafers with a polyimide (SiO$_2$) insulator were illuminated for 4 minutes (80 seconds). Solid lines are fits to the Boltzmann transport model described in section III, equation (1) and equations (9)–(12) with fit parameter values listed in Table II. Dashed lines (red or black) in panel (d) are fits to equation (15), describing transport near the 2D percolation threshold.

below the surface ($d = 250$ nm in Ref. [10], 150 nm in Ref. [13], and 185 nm in Ref. [34]). Their observations of increased post-illumination mobility on dedicated Hall bars are consistent with the data shown here. Likewise, a mobility increase after illumination was also observed in the other illumination study on HIGFETs [36], with their 2DEG located 115 nm below the surface.

The gain/loss in mobility shown in Figure 6 is persistent at low temperatures, lasting for weeks [58]. Furthermore, after a thermal cycle to room temperature and back to low temperatures, samples recover their dark transport characteristics, e.g. as shown in Figure 4(a). Sample E was illuminated during the first cooldown, cycled to room temperature, and cooled down again. Its transport characteristics in both cooldowns are nearly identical. In other words, like their modulation-doped cousins, dopant-free 2DEGs display the persistent photoconductivity effect.

We now turn to modeling to gain insight, using equation (1) in conjunction with eqns. (9)–(12). Model parameters for each wafer, such as the 2DEG depth $d$, are listed in Table II. The parameters $d$, $\Delta$, and $\Lambda$ do not change between before and after illumination.

For all wafers, we set $N_{bi-1} = N_{bi-2} = \overline{N_{bi}}$, the average background impurity concentration. When fitting the mobilities of W639/W640/W641 (from Series I) before/after illumination, the same $\overline{N_{bi}}$ was imposed on all three wafers, and surface charge density $N_{sc}$ was used as the only unrestricted free variable. Best fits were obtained by minimizing the sum of squared differences between experiment and theory. Parameter values for the best fit are listed in Table II. For the Series II wafers (G370/G372/G373/G404), both $\overline{N_{bi}}$ and $N_{sc}$ were used as unrestricted free variables for fitting mobilities in each
TABLE II. List of parameters used to model the 2DEG mobilities shown in Figure 6, before and after illumination (dark/light):

| Wafer ID | $d$ (nm) | $\Delta$ (nm) | $\Lambda$ (nm) | $N_{th}$ (cm$^{-3}$) | $N_{sc}$ (cm$^{-2}$) | $\Delta V_{th}$ (V) |
|----------|--------|----------|----------|----------------|----------------|--------------|
| V627$^a$ | 30     | 0.11     | 15       | $6.8 \times 10^{14}$ | $2.5 \times 10^{14}$ | $+0.9$       |
| W639     | 160    | 0.15     | 14       | $1.3 \times 10^{14}$ | $<1 \times 10^{10}$ | $+1.7$       |
| W640     | 110    | 0.11     | 14       | $1.3 \times 10^{14}$ | $0.2 \times 10^{11}$ | $+3.4$       |
| W641     | 60     | 0.11     | 14       | $1.3 \times 10^{14}$ | $1.7 \times 10^{11}$ | $+1.3$       |
| G404     | 310    | 0.07     | 9        | $9.7 \times 10^{13}$ | $<1 \times 10^{10}$ | $+1.0$       |
| G373     | 160    | 0.10     | 16       | $1.1 \times 10^{14}$ | $<1 \times 10^{10}$ | $+1.1$       |
| G372     | 110    | 0.12     | 17       | $1.1 \times 10^{14}$ | $2.2 \times 10^{11}$ | $+1.1$       |
| G370     | 75     | 0.18     | 16       | $2.3 \times 10^{14}$ | $2.7 \times 10^{11}$ | $+1.3$       |
| error    | $\pm 1$ | $\pm 0.01$ | $\pm 1$ | $\pm 3\%$ | $\pm 3\%$ | $\pm 3\%$ | $\pm 0.02$ |

$^a$ For all the “G” wafers, the number cited in this column is the average of measurements from two Hall bars.

$^b$ This wafer is listed separately because it was grown in a different MBE chamber, part of another set described in Ref. [18].

$^c$ These uncertainties apply to the whole column.

wafer, if $N_{sc}$ was not negligible. For example, for wafer G404, $N_{sc}$ was negligible and a one-parameter fit ($N_{th}$) was sufficient to model its mobility both before and after illumination. Parameter values for the best fit are listed in Table II.

The first common theme surmised from Table II to all 2DEGs from the “W” and “G” wafer series is that illumination appears to reduce the net average density of ionized/charged background impurities $N_{th}$, and is responsible for the improved mobilities (by up to +25%, at the same electron density) in the 2DEGs that are 75 nm or more away from the surface. One must therefore answer the question: what type of charged/ionized impurities can, upon illumination, be converted into neutral ones?

The usual candidate for the persistent photoconductivity effect in modulation-doped GaAs/AlGaAs 2DEGs are DX centers in AlGaAs [59, 60], deep traps consisting of a single impurity atom and an associated crystal lattice deformation. They are often linked to Si impurities, the most common intentional $n$-type dopant in GaAs/AlGaAs 2DEGs, but can also arise from other impurity atoms such as Ge, Sn, Se, S, and Te [59]. Of these, we will mostly focus on Si in the present discussion, the most studied and a likely background impurity in our MBE chambers due to the presence of Si effusion cells. We note however that sulfur is one of the two most common impurities present in high-purity arsenic sources [61–63] (the other being carbon), and has been predicted to form DX$^-$ centers in both AlGaAs [59] and GaAs [64, 65].

Scenarios involving the conversion of negatively-charged DX$^-$ centers into neutral shallow donors ($d^0$) through illumination could potentially explain our observations. One such scenario could be $DX^- + d^+ \rightarrow 2d^0$, as observed in modulation-doped GaAs/AlGaAs 2DEGs [66, 67], in which two ionized impurities before illumination are converted into two neutral impurities after illumination by transferring an electron $e^-$ from the DX center to the ionized shallow donor $d^+$. The resulting reduced scattering from $N_{th}$ would increase the mobility at a given carrier concentration. Furthermore, since the bandstructure in our samples is essentially flat at $V_{topgate} = 0$, there is no energy barrier preventing free electrons in AlGaAs from migrating to GaAs. This is not the case in modulation-doped GaAs/AlGaAs heterostructures. Shallow donors in GaAs could therefore be available to receive electrons released by the neutralized DX centers in the AlGaAs. This would in turn reduce $N_{th}$ (background impurities in GaAs), which would have more impact on mobility than neutralizing a shallow donor in AlGaAs.

However, the shallow neutral donor state of Si dopants is not stable, and is known to decay back to a positively-charged state $d^0 \rightarrow d^+ + e^-$ after some time [60, 66], ranging from seconds to tens of hours [68]. It cannot revert back to the DX$^-$ state. Similarly, Silicon’s neutral deep donor state $DX^0$ (obtained by $DX^- \Rightarrow DX^0 + e^-$ after illumination) is also metastable, and reverts back to either DX$^-$ (through thermal electron re-capture) or $d^+$ (through further photo-ionization) [60]. This naturally leads one to ask the following two questions about the experiments of Figure 6. Did metastable states play a major role in the mobility increase? On the other hand, were the measurements after illumination performed with all impurities in a new equilibrium state?
Instead reduce doped 2DEGs (for a constant carrier density) [67], but distribution is known to increase mobility in modulation-states after illumination. This type of change in impurity after DX-like centers into d+ states could be consistent with our experimental data.

Other scenarios involving exotic deep donor DX complexes or DX-like states cannot be ruled out, and could be consistent with our experimental data and modeling. For example, one could speculate that the long-lived neutral deep-donor DX0-like state in GaAs after illumination (DD0), reported by Carey et al. [71], could fulfill a similar role as the short-lived d0 state in the processes/reactions discussed above, i.e. DX− ⇒ DD0 + e−. Such a process taking place in GaAs, where the 2DEG resides, would have much more impact on mobility than in AlGaAs, relatively far away from the 2DEG.

Is there another type of impurity – other than deep donor DX centers – that would, upon illumination, transition from a charged state to a neutral state in both GaAs and AlGaAs, and cause a persistent photoconductivity effect? A. M. See et al. [34] have proposed charge neutralization of ionized carbon impurities could fit these requirements. Carbon atoms are common background impurities in MBE chambers and are present in both AlGaAs and GaAs [61–63]. Photoluminescence studies have identified deep acceptor states associated with carbon [61]. Persistent photoconductivity has been reported after illumination of carbon modulation-doped GaAs/AlGaAs two-dimensional holes gases (2DHG) [72–74]. This strongly suggests the existence of deep acceptor states associated with a lattice deformation (negative-U model), so-called “AX centers”. These are predicted for carbon impurities in AlGaN alloys [75], but could be possible in other III-V materials [76], raising the possibility of the illumination reaction AX+ + a− ⇒ 2a0 [75], where a− (d0) is a charged (neutral) shallow acceptor. In our experiments, the two-step mechanism for charge neutralization would first involve the band-to-band optical excitation of an electron trapped in an a− impurity in either GaAs or AlGaAs, since the photon energy of the red LED (∼2 eV) exceeds the bandgaps of both GaAs (∼1.5 eV) and AlGaAs (∼1.9 eV). Second, the liberated electron is captured by a nearby AX+ center, in GaAs or AlGaAs. This process would thus convert two charged impurity states (a−, AX+) into two neutral ones (a0), and increase mobility. For the above mechanism to be viable, the a0 state after illumination must be stable in time. Another requirement for this mechanism’s viability is that most carbon impurities must already be ionized before illumination. This is indeed the case: Giannini et al. reported ionization rates of more than 80% for carbon impurities in GaAs and AlGaAs [77], while ionization rates of up to 100% have been reported if the carbon doping density is less than 3×1017 cm−3 [78], the relevant regime in the samples presented here. Thus, charge neutralization of acceptor impurities after illumination could be consistent with our experimental data and modeling.

The second common theme surmised from Table II is that illumination appears to increase the surface charge density. This could be caused by the activation of surface states/traps by light. Another possible cause is the
accumulation of electrons at the surface for the sample to maintain overall charge neutrality, because of electrons released by impurities (such as DX centers) or band-to-band photo-excited electrons. In 7 out of 9 bipolar samples from Series II where transport properties of 2DHGs were also measured, the observed change before/after illumination in threshold voltage $\Delta V_{th}$ of 2DHGs were also measured, the observed change bipolar samples from Series II where transport properties of 2DHGs were also measured, the observed change increase in surface charge density is larger for the shallower 2DEGs, and this is reflected in both the “W” and “G” process in Fig. 6(d) with data from the lower mobility range can be fit to equation (15) [black dashed line in Fig. 6(d)], and data from the upper mobility range can be fit to equations (9) with parameters listed in Table II [black solid line in Fig. 6(d)], and data from the lower mobility range can be fit to equation (15) [black dashed line in Fig. 6(d)] with $A_0 = 2.89 \times 10^{-2}$ cm$^2$/Vs and $n_c = 1.9 \times 10^{10}$ /cm$^2$. The critical density $n_c$ is higher after illumination than that before illumination, consistent with the observed decrease in mobility due to the corresponding increase in disorder.

B. Biased illumination, while $V_{topgate} \neq 0$

Since polyimide can leak when illuminated while $V_{topgate} \neq 0$, biased illumination was only performed on Hall bars from Series II, with a SiO$_2$ gate dielectric. Devices were cooled down in the dark, and illuminated at $T = 1.4$ K. In order to separate the effects of unbiased from biased illuminations, devices were initially illuminated for 6 minutes while keeping $V_{topgate} = 0$. Heat dissipation from the LED caused a nominal temperature increase of $T < 1.8$ K. After this initial illumination, subsequent biased illuminations were carried out by illuminating for one minute with the topgate held at finite voltage values. After the LED was turned off, the topgate was set to zero voltage, and the sample cooled back down to $T = 1.4$ K before measurements would begin. Thus, most biased illuminations on a particular device were performed during a single cooldown.

Akin to biased cooling [83–86], the density-topgate voltage functions $n_{2D}(V_{topgate})$ in Figures 9(a) and 9(b) are shifted by the voltage at which the topgate was held during illumination. For each device, the slopes of all $n_{2D}(V_{topgate})$ are the same as each other and the same as that for illumination at $V_{topgate} = 0$; the topgate-2DEG capacitance does not change. Remarkably, biased illu-

![FIG. 8. Schematic of the bandstructure of a hypothetical Hall bar from a Series I wafer (see Fig. 1) with a SiO$_2$ gate dielectric at $V_{topgate} = 0$ (not conducting): (a) before illumination, and (b) after illumination.](image)
FIG. 9. (color online) Electron density versus topgate voltage after multiple biased illuminations on: (a) shallow wafer G370, and (b) deep wafer G373. Symbols in all four panels are defined in panel (c), and are in the order of biased illuminations performed during the same cooldown, with ‘start’ being the first. In all cases, the electron density versus topgate voltage relation is shifted by the voltage at which the biased illumination was performed. Note how the characteristics of the initial 0 V biased illumination (red ‘+’ symbols) are recovered when another biased illumination at \( V_{\text{topgate}} = 0 \) V is performed (black ‘x’ symbols) after three biased illuminations are performed at \( V_{\text{topgate}} = -2, -4, -6 \) V, and \(-6\) V. Electron mobilities after multiple biased illuminations are shown for a: (c) shallow wafer G370, and (d) deep wafer G373. For clarity, only a selection of biased illuminations are shown in these panels. The inset in panel (d) has the same axes and units as in the main figure; it is a magnified view of the data points near \( n_{2d} = 1.1 \times 10^{11}/\text{cm}^2 \).

mination appears to be a reversible process, relative to illumination at \( V_{\text{topgate}} = 0 \). This is illustrated in both Figures 9(a) and 9(b): after an initial illumination at \( V_{\text{topgate}} = 0 \) (red ‘+’ symbols), a series of biased illuminations are performed before repeating an illumination at \( V_{\text{topgate}} = 0 \) (black ‘x’ symbols). The \( n_{2d}(V_{\text{topgate}}) \) function of the initial \( V_{\text{topgate}} = 0 \) illumination is recovered after the subsequent \( V_{\text{topgate}} = 0 \) illumination (the ‘+’ and ‘x’ symbols line up almost perfectly). Recovery of original characteristics is not limited only to the \( V_{\text{topgate}} = 0 \) illumination, as we have confirmed that \( n_{2d}(V_{\text{topgate}}) \) of any biased illumination at \( V_{\text{topgate}} = V_0 \) can be recovered by illuminating again with the same topgate voltage \( V_0 \).

Although the effects of biased illumination on mobility are small (with differences of up to 7% between the smallest and largest mobilities), these are still larger than measurement uncertainties (<3%). Figures 9(c) and 9(d) show transport measurements on two 2DEGs, located 75 nm and 160 nm below the wafer surface respectively. One observation is that, for both 2DEG depths, biased illuminations performed when \( V_{\text{topgate}} \geq +2 \) V increase mobility, whereas those performed when \( V_{\text{topgate}} \leq -2 \) V decrease mobility. A second observation is that the mobility changes are larger in the shallower 2DEG than in the deeper 2DEG. A third observation is that mobility changes are reversible for both shallow and deep 2DEGs, within the same cooldown.

In both Figures 9(c) and 9(d), after an initial illumination at \( V_{\text{topgate}} = 0 \) (red ‘+’ symbols), a series of biased illuminations are performed before repeating an illumination at \( V_{\text{topgate}} = 0 \) (black ‘x’ symbols). The mobility of the initial \( V_{\text{topgate}} = 0 \) illumination is recovered after a subsequent \( V_{\text{topgate}} = 0 \) illumination: the ‘+’ and ‘x’ symbols line up almost perfectly. The mobility gain/loss must be accounted for by a decrease/increase in electron scattering.

A possible culprit could be the gate dielectric. The amorphous SiO₂ layer contains a very large number of defects (relative to single crystal GaAs/AlGaAs), a fraction of which could populate or depopulate with electrons during biased illumination, in response to the finite topgate voltage. This certainly could explain the voltage shifts (equal to the topgate voltage value during biased illumination) in \( n_{2d}(V_{\text{topgate}}) \) observed in Figures 9(a) and 9(b). This scenario would also be consistent with the deeper 2DEGs experiencing smaller mobility gains/losses, since they are further away from the SiO₂ layer. Before illumination, the range of topgate voltages without hysteresis is restricted to approximately \( |V_{\text{topgate}}| \lesssim 5 \) Volts. However, after illumination (whether at \( V_{\text{topgate}} = 0 \) or \( V_{\text{topgate}} \neq 0 \)), the range of topgate voltages without hysteresis is extended to \( |V_{\text{topgate}}| \lesssim 9 \) Volts. This suggests illumination does introduce some changes.

FIG. 10. (color online) Electron mobilities for ambipolar sample L (with both n-type and p-type ohmic contacts) shown in Fig. 9(c), and close-up view of the multiple biased illuminations at \( V_{\text{topgate}} = -2, -4, -6, +4 \) V in chronological order. The two dashed lines are otherwise identical mobility simulations, except for a difference of \( \Delta N_{\text{sc}} = 8 \times 10^{10}/\text{cm}^2 \) in surface charge density, using the Boltzmann transport model described in section III. The two key features to note here are: (i) all the \( V_{\text{topgate}} < 0 \) biased illumination mobilities fall on the same mobility curve \( \mu(n_{2d}) \), and (ii) the mobility after the \( V_{\text{topgate}} = +4 \) V biased illumination increases.
to the SiO$_2$ layer (ionization of defects), and is consistent with the scenario depicted above.

However, Figure 10 presents a puzzle that cannot be explained by the scenario above. Upon close inspection, the mobilities after biased illuminations at $V_{\text{topgate}} = -2$ V, $-4$ V, and $-6$ V on sample L (wafer G370) all lie nearly on the same mobility curve $\mu(n_{2n})$. In other words, the mobility loss has saturated after the $V_{\text{topgate}} = -2$ V biased illumination, which implies that the number of scattering centers in the SiO$_2$ layer is no longer increasing with biased illuminations at more negative topgate voltages. Yet, the $n_{2n}(V_{\text{topgate}})$ relation in Figure 9(a) shows no signs of saturation, with ever larger topgate voltage shifts. The latter implies an increasing number of active defects in the SiO$_2$ layer from biased illuminations with increasing topgate voltages. Both statements cannot be simultaneously true.

To resolve the inconsistency outlined above, we propose that the behavior of the relation $n_{2n}(V_{\text{topgate}})$ is primarily affected by defect-driven charging effects in the SiO$_2$ layer, and that the behavior of the relation $\mu(n_{2n})$ is primarily affected by changes in surface charge density $N_{sc}$. In this new scenario, mobility increases (decreases) when the surface charge density decreases (increases) due to $V_{\text{topgate}} > 0$ ($V_{\text{topgate}} < 0$) biased illuminations. One possible mechanism for a gain in mobility is the (re-)capture of electrons by charged surface defects, facilitated by $V_{\text{topgate}} > 0$. The loss in mobility when $V_{\text{topgate}} < 0$ would correspond to further ionization of “dangling” bonds at the surface, i.e. the GaAs/SiO$_2$ interface. The saturation of mobility loss occurs when all available surface defects have been ionized.

Although there are far fewer available defects at the surface of single-crystal GaAs than in a 300 nm-thick amorphous SiO$_2$ layer, ionized impurities at the wafer surface are much more effective at scattering electrons: (i) they are physically much closer to the 2DEG, and, in the parlance used for quantum dot transport, (ii) they have a much bigger lever arm because of the higher relative dielectric constant in Al$_{0.3}$Ga$_{0.7}$As ($\epsilon_r \approx 12$) relative to our PECVD SiO$_2$ ($\epsilon_r \approx 3.5$). Recalling eqn. (10), the scattering rate of electrons in a 2DEG due to an ionized impurity is an exponentially decreasing function of distance. So, even if there are far more SiO$_2$ bulk defects than surface states (i.e. GaAs/SiO$_2$ interface states), the latter are exponentially more effective at increasing/decreasing the 2DEG mobility.

This new scenario is consistent with both mobility loss saturation (Fig. 10) and the decreasing effects of biased illumination with increasing 2DEG depth (Fig. 9). Next, we perform a sanity check on our proposed scenario. The mechanism for mobility gain after a $V_{\text{topgate}} > 0$ biased illumination explicitly relies on electron-hole photogeneration, the (re-)capture of photo-generated electrons by surface charge defects, and the presence of p-type ohmic contacts to sweep away the photo-generated holes. What if a sample does not have p-type ohmic contacts?

In that case, photo-generated holes would not be swept away by the p-type ohmic contacts, and would instead recombine with any available electrons, most likely the photo-generated electrons. The latter would thus not be available to be re-captured by ionized charge surface defects (i.e., $N_{sc}$ cannot decrease), and mobility would not increase any further. Figure 11 confirms that this is exactly what is observed in experiments on sample M, which has only n-type ohmic contacts but is otherwise identical in all other respects to samples from Series II. After an initial unbiased illumination (red ‘+’ symbols...
in Fig. 11), the mobility increases by 25% from mobilities in the dark (not shown). This mobility gain does not require the presence of p-type ohmics. Next, a series of biased illuminations with \( V_{\text{topgate}} < 0 \) (‘\( \odot \)’, ‘\( \bigtriangleup \)’, and ‘\( \odot \)’ symbols) are carried out, with mobility loss due to the increase in surface charge density (the ionization of all remaining charge surface defects) in Figs. 11(a) and 11(b). This also does not require the presence of p-type ohmic contacts. All mobilities fall onto the same curve [Fig. 11(a)]. Lastly, two more biased illuminations are carried out, one at \( V_{\text{topgate}} = 0 \) (black ‘\( \times \)’ symbols) and one at \( V_{\text{topgate}} = +4 \text{ V} \) (‘\( \blacktriangle \)’ symbols). Unlike the ambipolar Hall bars in Figure 9, the mobility of the unipolar Hall bar does not recover/increase [Fig. 11(a)], but remains on the same \( \mu(N_{2d}) \) curve as that of the \( V_{\text{topgate}} < 0 \) biased illuminations [Fig. 11(b)], as predicted by our proposed scenario. Finally, Fig. 11(c) provides one last piece of evidence in favor of our scenario. After the \( V_{\text{topgate}} < 0 \) bias illuminations, the resulting ‘permanent’ (for this cooldown) increase in surface charge density \( N_{\text{sc}} \) causes a +0.33 V shift in \( n_{2d}(V_{\text{topgate}}) \) for the second \( V_{\text{topgate}} = 0 \) illumination (black ‘\( \times \)’ symbols), relative to the first \( V_{\text{topgate}} = 0 \) illumination (red ‘\( + \)’ symbols), to achieve the same electron density \( n_{2d} \). This is in direct contrast to behavior observed in ambipolar devices [Figs. 9(c) and 9(d)], where bias illuminations are fully reversible.

V. DISCUSSION AND CONCLUSION

The main result of section IV A indicates that unbiased illuminations can reduce scattering from ionized impurities concentration by up to 30% in dopant-free 2DEGs, for the same electron density. The exact mechanism(s) through which this occurs remain unclear. The conventional mechanism involving Si impurity DX centers could perhaps explain the increase in mobility at the same carrier density. Other types of donor DX or DX-like centers could not be ruled out, whether with silicon or other impurity species (e.g. sulfur). Speculation about acceptor AX centers from carbon impurities in GaAs/AlGaAs led to a mechanism that could be consistent with data shown, provided photo-neutralized shallow acceptor states (\( \odot \)) are stable at low temperature. Whichever mechanism underpins our observations, the observed increase in mobility would most likely also occur in high-mobility n-type modulation-doped 2DEGs and p-type modulation-doped 2DHGs.

Unbiased illumination is commonly used in fractional quantum Hall effect (FQHE) experiments in modulation-doped 2DEGs to improve the activation energies of FQHE states. Both the electron density and mobility increase significantly via the persistent photoconductivity effect. Interestingly, Samani et al. [87] were able to use a two-step unbiased illumination protocol that drastically improved their samples’ FQHE characteristics, while retaining the same electron density and mobility as before illumination. Their samples use a delta-doping scheme that places Si dopants in GaAs “doping” wells [63, 88], thus preventing the formation of DX centers. The improvement of their FQHE states after illumination is attributed to enhanced screening from dopant-dopant correlations [84, 89], in a manner very reminiscent of overdoping [88]. Could dopant-dopant correlations occur in dopant-free 2DEGs? This appears very unlikely. The Si delta-doping sheet density in the modulation-doped 2DEGs mentioned above is \((1 - 2) \times 10^{12} \text{ cm}^{-2}\), which corresponds to an average dopant-dopant separation of \( 8 - 11 \text{ nm} \). With such proximity, strong correlations between dopants are indeed likely. In dopant-free 2DEGs, the background impurity volume density is of order \((1 - 2) \times 10^{14} \text{ cm}^{-3}\) or less, which corresponds to an impurity-impurity average separation of 450 – 570 nm. Dopant-dopant correlations (and therefore screening) are unlikely to play a major role in the experiments described in this paper. Nevertheless, it would be interesting to observe the effects of illumination on FQHE states in a dopant-free 2DEG.

After an initial unbiased illumination, the effects of additional, biased illuminations (section IV B) on mobility \( \mu(N_{2d}) \) are very limited, with changes of \( \sim 5\% \) at most for a narrow range of gate voltages. Outside of that gate voltage range, \( \mu(N_{2d}) \) no longer responds to biased illuminations, for either gain or – unusually – loss. The saturation of mobility losses is attributed to the activation of all available defects/states at the interface between the GaAs cap layer and the SiO\(_2\) gate dielectric (the “surface”). Whether these states/defects are located on the gate dielectric or the semiconductor side of this interface cannot be distinguished. While \( \mu(N_{2d}) \) no longer responds to biased illuminations, \( n_{2d}(V_{\text{topgate}}) \) still does, with the change in 2DEG turn-on threshold voltage \( \Delta V_{\text{th}} \) exactly matching the \( V_{\text{topgate}} \) at which the biased illumination was performed. In that regard only (ignoring the saturation of mobility losses), biased illumination bears some resemblance with bias cooling [86], in that it can “lock in” a built-in electric potential. However, unlike bias cooling, this built-in electric potential can be arbitrarily tuned \textit{in-situ} during the \textit{same} cooldown (with additional biased illuminations), and most likely originates in the gate dielectric.

In conclusion, we have shown that unbiased \( (V_{\text{topgate}} = 0) \) and biased \( (V_{\text{topgate}} \neq 0) \) illuminations have different effects on dopant-free 2DEGs, and presented possible mechanisms explaining the observed behavior. Unbiased illuminations increase (decrease) the mobility at the same electron density if the 2DEG depth below the surface is more (less) than \( \sim 70 \text{ nm} \). Whether mobility increases or decreases results from the interplay between the reduction of charged background ionized impurities \( (N_{\text{bi}}) \), and the increase in surface charge density \( (N_{\text{sc}}) \) after illumination. Biased illuminations increase (decrease) mobilities, regardless of 2DEG depth, if the topgate voltage \( V_{\text{topgate}} > 0 \) \( (V_{\text{topgate}} < 0) \), and is primarily driven by changes in surface charge density \( (N_{\text{sc}}) \). The magnitude of the mobility gain/loss is larger (smaller) for
2DEGs that are close to (far from) the wafer surface. Remarkably, the effects of any specific biased illumination are fully reversible, both in mobility and 2DEG turn-on threshold voltages.

ACKNOWLEDGMENTS

A.S., F.S., and W.Y.M. contributed equally to this work. The authors thank Christine Nicoll for illuminating discussions. I.F. thanks Toshiba Research Europe for financial support. This research was undertaken thanks in part to funding from the Canada First Research Excellence Fund (Transformative Quantum Technologies), Defence Research and Development Canada (DRDC), Canada’s National Research Council (NRC) under contract W943741, Canada’s Natural Sciences and Engineering Research Council (NSERC), as well as the UK’s Engineering and Physical Research Council grants EP/K004077/1 and EP/J003417/1. The University of Waterloo’s QNFCF facility was used for this work. This infrastructure would not be possible without the significant contributions of CFREF-TQT, CFI, ISED, the Ontario Ministry of Research and Innovation, and Mike and Ophelia Lazaridis. Their support is gratefully acknowledged.

Appendix A: Interface Roughness

The GaAs/AlGaAs interface where the 2DEG resides is not a perfectly smooth planar boundary, but consists instead of a textured plane where the electric field/barrier height have discontinuities in the plane. This interface roughness is characterized by the height \( \Delta \) of irregularities (be it crystal defects, atomic steps, or other) in the \( z \) direction and the separation distance \( \Lambda \) between these irregularities in the \( r \) direction [see Fig. 3]. The distribution of heights \( \Delta(r) \) along the interface is assumed to be Gaussian: \(< \Delta(r)\Delta(r') > = \Delta^2 e^{-(r-r')^2/\Lambda^2} \). The effects of interface roughness are more pronounced at higher carrier densities: as the carrier density increases, the electron wavefunction increasingly overlaps with the interface, and thus scattering increases. The wafer surface is used as a proxy for the GaAs/AlGaAs interface, and is characterized using an atomic force microscope (AFM), extracting values for \( \Delta \) and \( \Lambda \).

The scattering potential \(|U(q)|^2\) for interface roughness is [49]:

\[
|U(q)|^2_{irr} = \pi(\Delta \Lambda)^2 \left( \frac{e^2}{\epsilon_0 \epsilon_r} \left( \frac{n_{2D} + N_{depl}}{2} \right) \right)^2 e^{-q^2 \Lambda^2/4} \tag{A1}
\]

which, after inserting the above expression in equation (8) and rewriting the integral in terms of \( d\theta \), gives [90]:

\[
\frac{1}{\tau_{irr}} = \frac{m^* (\Delta \Lambda)^2}{2\hbar^2 k_F^2} \int_0^{\pi} q^2 \frac{\Gamma(q)^2}{\epsilon(q)^2} e^{q^2 \Lambda^2/4} d\theta \tag{A2}
\]

with \( \Gamma(q) = \frac{e^2}{\epsilon_0 \epsilon_r} \left( \frac{n_{2D}}{2} + N_{depl} \right) \approx \frac{n_{2D} \epsilon_r^2}{2\epsilon_0 \epsilon_r} \tag{A3} \)

\[
N_{depl} = \sqrt{2\epsilon_0 \epsilon_r N_a E_g} \tag{A4}
\]

where \( N_{depl} \) is the depletion charge density, \( N_a \) is the acceptor concentration in the GaAs layer, and \( E_g \) is the bandgap in GaAs.

The depletion charge term arises if the material hosting the 2DEG is lightly p doped by impurity atoms (\( N_{irr} = 2 \) in GaAs for example) or implantation (as is often the case in Si-based devices). This changes the overall bandstructure and affects the position of the electron wavefunction. However, because \( \epsilon_{GaAs}^r \approx \epsilon_{AlGaAs}^r \) is assumed, the term \( \Gamma(q) \) no longer depends on \( \theta \) via the \( \sin^2 \theta \) term in \( q \) and it can be pulled out of the \( d\theta \) integral. Furthermore, since the background impurity concentration (\( N_{irr} \)) is much less than the carrier density (\( n_{2D} \)) in the experiments studied in this paper, i.e. \( N_{irr} \ll \frac{1}{2} n_{2D} \), we approximate \( N_{depl} \approx 0 \) so that \( \Gamma(q) = \frac{n_{sc} \epsilon_r^2}{2\epsilon_0 \epsilon_r} \) in equation (A3) and equation (9).

Appendix B: Surface Charge

Charge can accumulate at the surface of semiconductors for a variety of reasons, be it from the local reorganization of the crystal lattice and bandstructure, redistribution of free charges (e.g., from ionized impurities), or the presence of excited states/dangling bonds to name a few. In GaAs/AlGaAs heterostructures at low temperatures, these surface charges are usually not mobile and their sheet density has been shown to be constant [12], consistent with the “frozen surface model”. If the 2DEG is close to the surface (2DEG depth below the surface is \( |d| \lesssim 100 \) nm), these surface charges cause scattering to 2DEG carriers through Coulomb interactions [18, 22], as illustrated in Figure 12.

Model-wise, surface charges are treated the same way as a delta-doped layer in a modulation-doped structure, located at the surface [47, 49]. Therefore the scattering potential \(|U(q)|^2\) for surface charge becomes:

\[
|U(q)|^2_{sc} = N_{sc} \left( \frac{e^2}{2\epsilon_0 \epsilon_r q} \right)^2 \frac{e^{-2q|d|}}{(1 + q/b)^6} \tag{B1}
\]

where \( N_{sc} \) is the surface charge sheet density and the rightmost fraction is the form factor \( F_1(q, d)^2 \) obtained from [18, 47, 52, 92]:

\[
F_1(q, z) = \int_0^\infty |\psi(z')|^2 e^{-q|z-z'|} dz' \tag{B2}
\]

\[
F_1(q, d) = e^{-q|d|} \left( \frac{b}{b + q} \right)^3 = \frac{e^{-q|d|}}{(1 + q/b)^3} \tag{B3}
\]
eqn. (8) and rewriting the integral in terms of $d\theta$ gives:

$$
\frac{1}{\tau_{\text{bi}-1}} = \frac{N_{\text{bi}}}{2\pi \hbar^3 k_F^2} \left( \frac{e^2}{2e_\text{F} q} \right)^2 \int_0^\pi \frac{e^{-2qd|z|}}{\epsilon(q)^2 (1 + q/b)^6} d\theta.
$$

**Appendix C: Background Impurities in AlGaAs**

Impurity atoms are invariably incorporated into semiconductor heterostructures during MBE growth. These can be either intentional dopants (for modulation doping) or non-intentional dopants (background impurities). In the dopant-free wafers considered here, only non-intentional background impurities are present, characterized by a volume impurity concentration $N_{\text{bi}}$. Ionized impurity scattering tends to dominate over other forms of scattering at very low carrier densities (e.g., interface roughness scattering or alloy scattering). Background impurity scattering from the AlGaAs and GaAs layers are treated separately in our model.

To quantify Coulomb scattering from impurities in the AlGaAs barrier, eqn. (B1) for a delta-doped layer is integrated over the AlGaAs barrier volume (semi-infinite layer approximation), replacing $|d|$ with $|z|$, yielding the following scattering potential:

$$
|U(q)|^2 = \left( \frac{e^2}{2e_\text{F} q} \right)^2 \int_0^\infty N_{\text{AlGaAs}}^{2D} e^{-2q|z|} \epsilon_{2D} d\theta (C1)
$$

$$
= N_{\text{bi}-1} \left( \frac{e^2}{2e_\text{F} q} \right)^2 F_{\text{AlGaAs}}(q) (C2)
$$

where $N_{\text{AlGaAs}}^{2D}$ is the 2D sheet concentration of impurities in the AlGaAs layer, $N_{\text{bi}-1}$ is the volume impurity concentration in the AlGaAs layer, and $F_{\text{AlGaAs}}(q)$ is:

$$
F_{\text{AlGaAs}}(q) = \int_0^\infty F_1(q, z')^2 d'z' = \frac{1}{2q(1 + q/b)^6} . (C3)
$$

where $F_1(q, z')$ is defined in eqn. (B3) with $z' > 0$. Substituting eqn. (C2) into eqn. (8), simplifying and rewriting the integral in terms of $d\theta$ gives:

$$
\frac{1}{\tau_{\text{bi}-1}} = N_{\text{bi}-1} m^* \frac{\hbar^3 k_F^2}{2e_\text{F} q} \left( \frac{e^2}{2e_\text{F} q} \right)^2 \int_0^\pi \frac{F_{\text{AlGaAs}}(q)}{\epsilon(q)^2} d\theta . (C4)
$$

**Appendix D: Background Impurities in GaAs**

Similarly to the treatment above for the AlGaAs layer, the $|U(q)|^2$ term for scattering from a strictly 2D charge layer (zero thickness) in the GaAs layer is:

$$
|U(q)|^2 = N_{\text{GaAs}}^{2D} \left( \frac{e^2}{2e_\text{F} q} \right)^2 F_2(q, z)^2 (D1)
$$

where $N_{\text{GaAs}}^{2D}$ is the 2D sheet density of impurities in the GaAs layer, $z$ is the coordinate of the 2D charge plane, and eqn. (B2) is used to calculate the form factor $F_2(q, z)$ for a 2DEG interacting with a 2D charge layer located in the same GaAs layer [47, 51]:

$$
F_2(q, z)_{|q=b} = \frac{1 + 2b + 2b^2 z^2 + \frac{3}{8} b^3 z^3}{8e^2 z} (D2a)
$$

$$
F_2(q, z)_{|q\neq b} = \frac{e^{(b-q)z} - (c_0 + c_1 z + c_2 z^2)}{(1 - q/b)^3 e^{bz}} (D2b)
$$
concentrations. Electron mobilities, at $T = 1.5$ K in the dark, of 310 nm deep 2DEGs before (squares) and after (circles) the growth of some $\sim 50$ wafers in the: (a) ‘A’ chamber and (b) ‘V’ chamber. Experimental data taken from Ref. 91. Solid (red) lines are fits from the model in section III with the parameters listed in Table IV. The average background impurity concentration $N_{bi}$ dropped from $3.3 \times 10^{14}$ /cm$^3$ in wafer A2460 to $1.3 \times 10^{14}$ /cm$^3$ in wafer A2513 in chamber ‘A’, and from $1.3 \times 10^{14}$ /cm$^3$ in wafer V535 to $0.7 \times 10^{14}$ /cm$^3$ in wafer V581 in chamber ‘V’.

\[
\begin{align*}
U(q)_{int-2}^2 &= \left( \frac{e^2}{2 \epsilon_0 \epsilon_r q} \right)^2 \int_0^\infty N_{GaAs}^{2D} \, F_2(q, z)^2 \, dz \\
&= N_{bi} \left( \frac{e^2}{2 \epsilon_0 \epsilon_r q} \right)^2 \, F_{GaAs}(q)
\end{align*}
\]

where $z > 0$. The expression for $F_2(q, z)$ is more complex than $F_1(q, z)$ owing to the direct overlap of the 2DEG wavefunction and the charge layer.

To quantify Coulomb scattering from impurities in the GaAs layer, eqn. (D1) is integrated over the GaAs layer (assuming a semi-infinite layer), yielding this scattering potential:

\[
F_{GaAs}(q)|_{q=b} = \frac{69}{128 q}
\]

where $c_0 = \frac{2q(3b^2 + q^2)}{(b + q)^3}$

\[
c_1 = \frac{4bq(b - q)}{(b + q)^2}
\]

\[
c_2 = \frac{q(b - q)^2}{(b + q)}
\]

Substituting eqn. (D4) into eqn. (8) and simplifying/rewriting the integral in terms of $d\theta$ gives:

\[
\frac{1}{\tau_{bi-2}} = \frac{N_{bi-2} m^*}{2\pi \hbar^2 k_F^2} \left( \frac{e^2}{2 \epsilon_0 \epsilon_r} \right)^2 \int_0^{\pi} F_{GaAs}(q) \frac{d\theta}{q(q^2)}
\]

In the case of deep 2DEGs (whose depth below the surface is greater than 300 nm), curve-fitting the mobility can be reduced to a single free variable (assuming experimentally-determined interface roughness terms $\Delta$ and $A$); the average background impurity concentration by setting $N_{bi} = N_{bi-1} = N_{bi-2}$. Single-parameter fits of four 2DEG mobilities as a function of electron density are shown in Figure 13.

### Appendix E: Relaxing $N_{bi-1} = N_{bi-2}$

Table V lists fit parameters to Series I wafers when the constraint $N_{bi-1} = N_{bi-2}$ is relaxed. As also found in Ref. 18 and Ref. 52, the ratio $N_{bi-1}/N_{bi-2}$ providing the
best fit to the data (all else being equal) was found to be approximately $\sim 3$, meaning there are about $3 \times$ more charged impurities in AlGaAs than in GaAs. Al atoms are more reactive than Ga atoms, and are thought to getter more impurities (most likely oxygen) [63].

[1] R. J. Nelson, Appl. Phys. Lett. 31, 351 (1977).
[2] H. L. Stormer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. 29, 705 (1979).
[3] H. L. Stormer, A. C. Gossard, and K. Baldwin, Appl. Phys. Lett. 39, 912 (1981).
[4] D. V. Lang and R. A. Logan, Phys. Rev. Lett. 39, 635 (1977).
[5] D. V. Lang, R. A. Logan, and M. Jaros, Phys. Rev. B 19, 1015 (1979).
[6] A. Kastalsky and J. C. M. Hwang, Solid State Commun. 51, 317 (1984).
[7] R. A. Stradling and W. Jantsch (editors), DX-centres and other metastable defects in semiconductors, Mauterndorf, Austria, 18-22 February 1991, conf. proc. in Semicond. Sci. Technol. 6 (10B), B1-B153 (1991).
[8] V. Yu, M. Hilke, P. J. Poole, S. Studenikin, and D. G. Austing, Phys. Rev. B 98, 165434 (2018).
[9] B. E. Kane, L. N. Pfeiffer, K. W. West, and C. K. Harrett, Appl. Phys. Lett. 63, 2132 (1993).
[10] T. Saku, K. Muraki, and Y. Hirayama, Jpn. J. Appl. Phys. 37, L765 (1998).
[11] Y. Hirayama, K. Muraki, and T. Saku, Appl. Phys. Lett. 72, 1745 (1998).
[12] A. Kawaharazuka, T. Saku, C. A. Kikuchi, Y. Horikoshi, and Y. Hirayama, Phys. Rev. B 63, 245309 (2001).
[13] Y. Hirayama, K. Muraki, A. Kawaharazuka, K. Hashimoto, and T. Saku, Physica E 11, 155 (2001).
[14] M. P. Lilly, J. L. Reno, J. A. Simmons, I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, K. W. West, E. H. Hwang, and S. Das Sarma, Phys. Rev. Lett. 90, 056806 (2003).
[15] A. Valeille, K. Muraki, and Y. Hirayama, Appl. Phys. Lett. 92, 152106 (2008).
[16] R. H. Harrell, K. S. Pyshkin, M. Y. Simmons, D. A. Ritchie, C. J. B. Ford, G. A. C. Jones, and M. Pepper, Appl. Phys. Lett. 74, 2328 (1999).
[17] R. L. Willett, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. 89, 242107 (2006).
[18] W. Y. Mak, K. Das Gupta, H. E. Beere, I. Farrer, F. Sfigakis, and D. A. Ritchie, Appl. Phys. Lett. 97, 242107 (2010).
[19] W. Pan, N. Masuhara, N. S. Sullivan, K. W. Baldwin, K. W. West, L. N. Pfeiffer, and D. C. Tsui, Phys. Rev. Lett. 106, 206806 (2011).
[20] J. C. H. Chen, D. Q. Wang, O. Klochan, A. P. Micolich, K. Das Gupta, F. Sfigakis, D. A. Ritchie, D. Reuter, A. D. Wieck, and A. R. Hamilton, Appl. Phys. Lett. 100, 052101 (2012).
[21] A. F. Croxall, B. Zheng, F. Sfigakis, K. Das Gupta, I. Farrer, C. A. Nicoll, H. E. Beere, and D. A. Ritchie, Appl. Phys. Lett. 102, 082105 (2013).
[22] D. Q. Wang, J. C. H. Chen, O. Klochan, K. Das Gupta, D. Reuter, A. D. Wieck, D. A. Ritchie, and A. R. Hamilton, Phys. Rev. B 87, 195313 (2013).
[23] S. Peters, L. Tiemann, C. Reichl, and W. Wegscheider, Phys. Rev. B 94, 045304 (2016).
[24] A. F. Croxall, F. Sfigakis, J. Walidie, I. Farrer, and D. A. Ritchie, Phys. Rev. B 99, 195420 (2019).
[25] D. J. Reilly, G. R. Facer, A. S. Dzurak, B. E. Kane, R. G. Clark, P. J. Stiles, R. G. Clark, A. R. Hamilton, J. L. O’Brien, N. E. Lumpkin, L. N. Pfeiffer, and K. W. West, Phys. Rev. B 63, 121311(R) (2001).
[26] O. Klochan, W. R. Clarke, R. Danneau, A. P. Micolich, L. H. Ho, and A. R. Hamilton, Appl. Phys. Lett. 89, 092105 (2006).
[27] S. Sarkozy, F. Sfigakis, K. Das Gupta, I. Farrer, D. A. Ritchie, G. A. C. Jones, and M. Pepper, Phys. Rev. B 79, 161307(R) (2009).
[28] A. M. See, O. Klochan, A. R. Hamilton, A. P. Micolich, M. Aagesen, and P. E. Lindelof, Appl. Phys. Lett. 96, 112104 (2010).
[29] O. Klochan, A. P. Micolich, A. R. Hamilton, K. Trunov, D. Reuter, and A. D. Wieck, Phys. Rev. Lett. 107, 076805 (2011).
[30] W. Y. Mak, F. Sfigakis, K. Das Gupta, O. Klochan, H. E. Beere, I. Farrer, J. P. Griffiths, G. A. C. Jones, A. R. Hamilton, and D. A. Ritchie, Appl. Phys. Lett. 102, 103507 (2013).
[31] A. Bogan, S. A. Studenikin, M. Korkusinski, G. C. Aers, L. Gaudreau, P. Zawadzki, A. S. Sachrajda, L. A. Tracy, J. L. Reno, and T. W. Hargett, Phys. Rev. Lett. 118, 167701 (2017).
[32] A. Bogan, S. A. Studenikin, M. Korkusinski, L. Gaudreau, P. Zawadzki, A. S. Sachrajda, L. A. Tracy, J. L. Reno, and T. W. Hargett, Phys. Rev. Lett. 120, 207701 (2018).
[33] A. M. See, I. Pilgrim, B. C. Scannell, R. D. Montgomery, O. Klochan, A. M. Burke, M. Aagesen, P. E. Lindelof, I. Farrer, D. A. Ritchie, R. P. Taylor, A. R. Hamilton, and A. P. Micolich, Phys. Rev. Lett. 108, 196807 (2012).
[34] A. M. See, A. R. Hamilton, A. P. Micolich, M. Aagesen, and P. E. Lindelof, Phys. Rev. B 91, 085417 (2015).
[35] During the peer review of this paper, Ref. 36 on illumination in HIGFETs was published.
[36] T. Fujita, R. Hayashi, M. Kohda, J. Ritzmann, A. Ludewig, A. D. Wieck, and A. Oiwa, J. Appl. Phys. 129, 234301 (2021).
[37] T. Fujita, K. Morimoto, H. Kiyama, G. Allison, M. Larson, A. Ludewig, S. R. Valentijn, A. D. Wieck, A. Oiwa, and S. Tarucha, Nat. Commun. 10, 2991 (2019).
[38] T. K. Hsiao, A. Rubino, Y. Chung, S. K. Son, H. Hou, J. Pedros, A. Nasir, G. Ethier Majcher, M. J. Stanley, R. T. Phillips, T. A. Mitchell, J. P. Griffiths, I. Farrer, D. A. Ritchie, and C. J. B. Ford, Nat. Commun. 11, 917 (2020).
[39] M. D. Blumenthal, B. Kaestner, L. Li, S. P. Giblin, T. J. B. M. Janssen, M. Pepper, D. Anderson, G. A. C. Jones, and D. A. Ritchie, Nat. Phys. 3, 343 (2007).
[40] B. Buonacorsi, F. Sfigakis, A. Shetty, M. C. Tam, H. S. Kim, S. R. Harrigan, F. Hohls, M. E. Reimer, Z. R. Wasilewski, and J. Baugh, Appl. Phys. Lett. 119, 114001 (2021).
Wafer lengths of the lattice constant, and of the bandgap of (Ga,Al)As relative to AlGaN may favor the formation of a stable AX center in (Ga,Al)As.

The larger sizes of the As atom (linked to covalent bond lengths), of the lattice constant, and of the bandgap of (Ga,Al)As relative to AlGaN may favor the formation of a stable AX center in (Ga,Al)As.

In fact, there is a very small increase (by +0.6%) in the mobility over 3 days for \( n_{2D} \approx 2.846 \times 10^{11} / \text{cm}^2 \) and \( n_{2D} \approx 2.203 \times 10^{11} / \text{cm}^2 \) (but not for \( n_{2D} \approx 1.557 \times 10^{11} / \text{cm}^2 \)). This mobility increase appears real: it is not due to drift of the gating characteristics of the SiO\(_2\) dielectric, because the density decreases (by −0.5%) over the same 3-day period. All else being equal, one would expect mobility to decrease if the density decreases in this sample, see Fig. 6(g). In any case, this small mobility increase pales in comparison to the large mobility increase (up to +30%) immediately after illumination, confirming that metastable shallow donors play only a minor role in our observations.

In typical modulation-doped 2DEGs, the \( d^0 \) state’s lifetime depends on the tunneling rate through the AlGaAs barrier separating the impurity from the 2DEG.

[41] V.-T. Dai, S.-D. Lin, S.-W. Lin, J.-Y. Wu, L.-C. Li, and C.-P. Lee, Jpn. J. Appl. Phys. 52, 014001 (2013).

[42] V.-T. Dai, S.-D. Lin, S.-W. Lin, Y.-S. Lee, Y. Zhang, L.-C. Li, and C.-P. Lee, Opt. Express 22, 3811 (2014).

[43] Y. Chung, H. Hou, S.-K. Son, T.-K. Hsiao, A. Nasir, A. Rubino, J. P. Griffiths, I. Farrer, D. A. Ritchie, and C. J. B. Ford, 100, 245401 (2019).

[44] Wafer series I (Series II) were grown at the University of Cambridge (University of Waterloo).

[45] A. Matthiessen and C. Vogt, Philos. Trans. R. Soc. London 154, 167 (1864).

[46] T. Ihn, Semiconductor Nanostructures (Oxford University Press, 2010).

[47] J. H. Davies, The Physics of Low-dimensional Systems (Cambridge University Press, 1998).

[48] A. Gold, Phys. Rev. B 38, 10798 (1988).

[49] F. F. Fang and W. E. Howard, Phys. Rev. Lett. 16, 797 (1966).

[50] F. Stern and W. E. Howard, Phys. Review 54, 437 (1982).

[51] J. H. Davies, The Physics of Low-dimensional Systems (Cambridge University Press, 1998).

[52] A. Gold, Phys. Rev. B 38, 10798 (1988).

[53] F. F. Fang and W. E. Howard, Phys. Rev. Lett. 16, 797 (1966).

[54] F. Stern and W. E. Howard, Phys. Review 163, 816 (1967).

[55] S. J. MacLeod, K. Chan, T. P. Martin, A. R. Hamilton, A. See, A. P. Micolich, M. Aagesen, and P. E. Lindelof, Phys. Rev. B 80, 035310 (2009).

[56] The computer program written in C and a fitting routine written for MATLAB® is available at https://github.com/arjuntalk/2DEG-model.

[57] Hall bars from Series I (Series II) were measured at the University of Cambridge (University of Waterloo).

[58] This definition minimizes variations in turn-on voltages between individual ohmic contacts, related to fabrication parameters rather than the GaAs/AlGaAs material itself.

[59] The computer program written in C and a fitting routine written for MATLAB® is available at https://github.com/arjuntalk/2DEG-model.

[60] Atomic force microscopy analysis revealed wafer W640 had an unexpectedly larger interface roughness than the other two wafers of the series, accounting for its lower-than-expected mobility.

[61] A. Kawaharazuka, T. Saku, Y. Hirayama, and Y. Horikoshi, J. Appl. Phys. 87, 952 (2000).

[62] This was observed in sample H, measured before/after a university-wide shutdown due to COVID-19.

[63] P. M. Mooney, J. Appl. Phys. 67, R1 (1990).

[64] P. M. Mooney, Semicond. Sci. Technol. 6, B1 (1991).

[65] B. J. Skromme, S. S. Bose, B. Lee, T. S. Low, T. R. Lepkowski, R. Y. DeJure, G. E. Stillman, and J. C. M. Hwang, J. Appl. Phys. 58, 4685 (1985).

[66] E. C. Larkins, E. S. Hellman, D. G. Schlom, J. S. Davies, M. H. Kim, and G. E. Stillman, J. Cryst. Growth 81, 344 (1987).

[67] M. J. Manfra, L. N. Pfeiffer, K. W. West, R. de Picciotto, and K. W. Baldwin, Appl. Phys. Lett. 86, 162106 (2005).

[68] Atomic force microscopy analysis revealed wafer W640 had an unexpectedly larger interface roughness than the other two wafers of the series, accounting for its lower-than-expected mobility.

[69] Atomic force microscopy analysis revealed wafer W640 had an unexpectedly larger interface roughness than the other two wafers of the series, accounting for its lower-than-expected mobility.

[70] A. Kawaharazuka, T. Saku, Y. Hirayama, and Y. Horikoshi, J. Appl. Phys. 87, 952 (2000).

[71] This was observed in sample H, measured before/after a university-wide shutdown due to COVID-19.

[72] P. M. Mooney, J. Appl. Phys. 67, R1 (1990).

[73] P. M. Mooney, Semicond. Sci. Technol. 6, B1 (1991).

[74] B. J. Skromme, S. S. Bose, B. Lee, T. S. Low, T. R. Lepkowski, R. Y. DeJure, G. E. Stillman, and J. C. M. Hwang, J. Appl. Phys. 58, 4685 (1985).

[75] E. C. Larkins, E. S. Hellman, D. G. Schlom, J. S. Davies, M. H. Kim, and G. E. Stillman, J. Cryst. Growth 81, 344 (1987).

[76] M. J. Manfra, L. N. Pfeiffer, K. W. West, R. de Picciotto, and K. W. Baldwin, Appl. Phys. Lett. 86, 162106 (2005).

[77] Atomic force microscopy analysis revealed wafer W640 had an unexpectedly larger interface roughness than the other two wafers of the series, accounting for its lower-than-expected mobility.

[78] A. Kawaharazuka, T. Saku, Y. Hirayama, and Y. Horikoshi, J. Appl. Phys. 87, 952 (2000).

[79] This was observed in sample H, measured before/after a university-wide shutdown due to COVID-19.

[80] P. M. Mooney, J. Appl. Phys. 67, R1 (1990).

[81] P. M. Mooney, Semicond. Sci. Technol. 6, B1 (1991).

[82] B. J. Skromme, S. S. Bose, B. Lee, T. S. Low, T. R. Lepkowski, R. Y. DeJure, G. E. Stillman, and J. C. M. Hwang, J. Appl. Phys. 58, 4685 (1985).

[83] E. C. Larkins, E. S. Hellman, D. G. Schlom, J. S. Davies, M. H. Kim, and G. E. Stillman, J. Cryst. Growth 81, 344 (1987).

[84] M. J. Manfra, L. N. Pfeiffer, K. W. West, R. de Picciotto, and K. W. Baldwin, Appl. Phys. Lett. 86, 162106 (2005).

[85] Atomic force microscopy analysis revealed wafer W640 had an unexpectedly larger interface roughness than the other two wafers of the series, accounting for its lower-than-expected mobility.

[86] A. Kawaharazuka, T. Saku, Y. Hirayama, and Y. Horikoshi, J. Appl. Phys. 87, 952 (2000).

[87] This was observed in sample H, measured before/after a university-wide shutdown due to COVID-19.
[92] A. Gold, Appl. Phys. Lett. 54, 2100 (1989).