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Electric field mapping of wide-bandgap semiconductor devices at a sub-micron resolution

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Electric fields drive the degradation of wide-bandgap semiconductor devices. However, directly mapping electric field inside an active device region remains challenging. Here, we show that electric-field-induced second harmonic generation can be used to map the electric field in the device channel of gallium nitride (GaN)-based high-electron-mobility transistors at a sub-micron resolution. To illustrate the capabilities of the approach, we used it to examine the impact of carbon impurity in the epitaxial buffer layer of the device. Carbon is a p-dopant in GaN and small changes in its concentration can dramatically change the bulk Fermi level, sometimes resulting in a floating buffer that is "short-circuited" to the device channel via dislocations. Our measurements show that, despite similar device terminal characteristics, very different electric field distributions can occur in devices with different carbon concentration. We also show that dislocation related leakage paths can lead to inhomogeneity in the electric field.

The electric field in electronic devices drives degradation phenomena, limiting their lifetime. This is true for all electronic devices but is particularly relevant in wide bandgap semiconductor devices which can be operated at higher voltages and electric fields than the traditional Si and GaAs device technology. For example, GaN high-electron-mobility transistors (HEMTs) typically exhibit lateral fields of 1-2 MV/cm which is more than 5 times higher than the breakdown field of Si devices. Electric field characterisation is therefore a high priority for understanding how devices work and their potential limitations and can inform the development of improved device designs. Technology computer aided design (TCAD) simulations are presently used to predict device operation, including electric field distribution, but quantitative experimental confirmation of these models is lacking. In fact, their calibration is normally based on current and voltage (*IV*) characteristics, sensed at the device terminals. However, this is a 'black box' measurement and it has been shown that different epitaxial dopant distributions can produce similar *IV* characteristics, but result in quite different electric field distributions within the device channel[1].

The AlGaN/GaN material system offers a high breakdown voltage, a high charge density two-dimensional electron gas (2DEG), high mobility and high thermal conductivity. HEMTs exploit these properties for high-power high-frequency radio frequency (RF) and power converter applications. However, their potential has not been fully realized because devices are de-rated in commercial applications to ensure long-term reliability. Challenges include current collapse[2], OFF state breakdown[3], and Joule heating[4]. For example, the high electric field at the drain side of the gate edge leads to gate leakage or hot electron injection under OFF state or power state stress which results in increased charge trapped in the barrier, on the surface, and in the buffer layer[5,6]. Negative charge trapping causes current collapse, deteriorating switch efficiency and decreasing output power. When the electric field strength in this region approaches the breakdown electric field, the device no longer operates reliably and correctly. Joule heating, which is due to electric field accelerated charge carrier scattering with phonons, determines the channel temperature distribution and thermal degradation during operation[7]. Detailed knowledge of the electric field distribution is required to address these challenges, but presently largely relies on simulation.

Experimentally, the absolute electric field strength in GaN HEMT devices has been inferred indirectly (such as from the measured temperature profiles[4,8,9], though this is not possible for OFF-state operation). Other approaches include using liquid crystal electrography[10] and Kelvin probe microscopy[11]. However, these are typically only sensitive to the electric field at the device surface and cannot be used to quantitatively measure the peak electric field, located *inside* the device active region. The Franz-Keldysh photocurrent spectroscopy technique[12,13], on the other hand, can only measure the magnitude of the electric field vector but not its orientation.

Orientation dependent electric field information can be extracted from electric field induced second harmonic generation (EFISHG) optical signals generated when a laser is incident on the device[14,15]. EFISHG is based on a two-photon process, related to the third-order nonlinear susceptibility $\chi^{(3)}$ of the material, the electric field of incident light and the applied electric field in the device. In the simplest case of a centrosymmetric semiconductor, the second-order nonlinear susceptibility $\chi^{(2)}$ is forbidden under the electric-dipole approximation. However, the presence of an electrical field breaks the symmetry of the semiconductor, and light at twice the frequency of the incident light can be generated from the fundamental frequency and detected, with an intensity related to the electric field strength. In centrosymmetric Si based devices including metal-oxide-semiconductor (MOS) capacitors and Si monolithic millimetre wave integrated circuits (MMICs), EFISHG was used to detect the occurrence of charge injection at interfaces and sample the high-speed electrical signals[16]. In organic devices, EFISHG signal has been used to visualize the carrier motion with a high temporal resolution[17,18]. The SHG light wavelengths in these works is usually above bandgap of the material, restricting measurements to the surface.

For non-centrosymmetric semiconductors such as GaN, SHG is dipole-allowed making the use of EFISHG much more challenging, although the presence of an electric field will increase or decrease its intensity[19,20]. Prior work on GaN HEMTs has shown that EFISHG can detect the presence of an electric field produced by trapped surface carriers in the on-state of the device, which leads to current collapse[21-25], but no quantification of the electric field was possible. The challenge in non-centrosymmetric materials is that the EFISHG signal is mixed with the field independent SHG signal and without careful extraction and calibration, quantification of electric field is impossible. A major benefit of wide bandgap semiconductor devices, such as GaN, is that they allow the SHG light to be below the bandgap, enabling the electric field distribution to be probed *within* the device, not only on its surface, with high spatial resolution.

In this article, we show that EFISHG can be used to quantitatively map the in-plane (E_x) electric field in non-centrosymmetric wide bandgap GaN devices. The effectiveness of the technique is demonstrated by showing that subtly different dopant distributions in the epitaxial device buffer layer can radically change electric field distribution *inside* the active region of the GaN-on-SiC HEMT. Our experimental results validate device simulations and highlight device behaviour that cannot be explained by *IV* characteristics alone.

Quantitative Electric Field Analysis of GaN HEMTs

For quantitative analysis, we must know the relationship between the applied electric field and the intensity of the measured SHG light, $I_{2\omega}$. This is greatly more complex for non-centrosymmetric material systems such as GaN, which have contributions from second and third-order non-linear susceptibility, intrinsic, and applied electric field induced SHG terms; AlGaN/GaN, for example, has a wurtzite crystal structure and 6mm point group symmetry, with 4 and 10 independent second and third-order susceptibility tensor components, respectively[26]. The laser polarization vector can be aligned parallel to the measured electric field vector between drain and source contacts, E_x, as shown in Fig. 1a. Assuming that light is focused into the device channel though a small solid angle (~10° for our experimental setup), the SHG intensity can be derived from[26]

$$I_{2\omega} \propto \left|P^{0}_{2\omega}+P^{\mathrm{EFISHG}}_{2\omega}\right|^{2} \propto \left|2\chi^{(2)}_{\mathrm{xzx}}E_{\mathrm{z},\omega}E_{\mathrm{x},\omega}+3\chi^{(3)}_{\mathrm{xxxx}}E_{\mathrm{x},\omega}E_{\mathrm{x},\omega}E_{\mathrm{x}}\right|^{2} \qquad (1)$$

where $\chi^{(2)}_{\mathrm{xzx}}$ and $\chi^{(3)}_{\mathrm{xxxx}}$ are the non-zero second and third-order non-linear susceptibility components, respectively; ω and 2ω are the fundamental and SHG frequencies, respectively; $I_{2\omega}$ is the total second harmonic signal, $P^{0}_{2\omega}$ and $P^{\mathrm{EFISHG}}_{2\omega}$ are field-independent and field-dependent second-order polarizations, respectively; $E_{\mathrm{x},\omega}$ and $E_{\mathrm{z},\omega}$ are the electric field components of the fundamental light, in the x and z-direction. We note that while the incident laser light is polarized in the x-direction, focusing will result in a small component in the z-direction. The discussion of other contributing terms of SHG signal can be found in Methods. In centrosymmetric semiconductors, $I_{2\omega}$ only relies on $P^{\mathrm{EFISHG}}_{2\omega}$, and usually has a quadratic[15] relationship with the applied field; this is because $P^{0}_{2\omega}$ from the bulk is zero. In our case, the total SHG depends on both $P^{0}_{2\omega}$ and $P^{\mathrm{EFISHG}}_{2\omega}$ causing the relationship with the applied field to be dependent on the cross term between $P^{0}_{2\omega}$ and $P^{\mathrm{EFISHG}}_{2\omega}$ taking into consideration interference between two nonlinear waves. The cross term of equation (1) can be neglected here as deduced from the bias dependence of the SHG intensity[19,20] (see Methods). Then, the electric field can be expressed as

$$E_{\mathrm{x}}=\alpha\left(\sqrt{I_{2\omega}-I_{2\omega}(E_{\mathrm{x}}=0)}\right) \tag{2}$$

where $I_{2\omega}(E_{\mathrm{x}}=0)$ is the fundamental SHG signal without an applied field (no bias voltage). The proportionality factor α in equation (2) corresponds to the optical detection efficiency, incident laser intensity and $\chi^{(3)}$, and is required for a quantitative electric field determination. This factor can be obtained by integrating the extracted in-plane electric field over the length of the channel and equating it to the gate-drain bias voltage. This is only possible when there is unobscured optical access to the whole device channel, achieved here using the back-side measurement scheme (Fig.1a). More details about the experimental calibration process relating to equation (2) are given in Methods, including how the intrinsic SHG $I_{2\omega}(E_{\mathrm{x}}=0)$ term is taken into account as well as the spatially varying surface reflectivity. Details about the Ti-sapphire laser and optical setup are also given in Methods and Extended Data Fig.1.

The extracted E_{x} gives a reasonable estimation of the electric field within the device channel. The measured EFISHG signal is convolved with the spatial resolution of the optical system. Since the peak electric field in a GaN HEMT, is normally expected to extend only 0.2-1.0 µm laterally from the drain side of the gate foot, high lateral spatial resolution is needed for accurate measurements. The measured lateral resolution using an 0.5 NA objective was 765±35nm (Extended Data Fig. 2), whereas the axial optical resolution is much larger than the GaN layer thickness (For details see Supplementary Note 1). However, the measurement is weighted to the highest E_x and $\chi^{(3)}$ region since the EFISHG signal is proportional to the square of these two factors when the cross term in equation (1) can be ignored. The electric field is mainly present in and very near to the device channel and hence this is where the measured EFISHG signal originates. The third-order nonlinear susceptibility of the AlGaN/GaN interface[27,28] was reported to be two orders of magnitude larger than that of GaN[29] and SiC[30], and three orders of magnitude larger than Si_3N_4[31]. This means the EFISHG signal from the channel region dominates over the signal from Si_3N_4 passivation, GaN buffer and SiC substrate layers; electric field determined then reflects channel in-plane electric field averaged over the lateral spatial resolution.

Impact of carbon impurity on the electric field in GaN HEMTs

To demonstrate the electric field quantification ability as well as the sensitivity of the technique to different electric field distributions, the EFISHG technique was applied to high-performance iron (Fe) doped GaN RF HEMTs on SiC with 0.25µm gate length (Fig. 1b) suitable for operation at X-band (10GHz), with current-voltage curves shown in Fig. 1c and 1d. The two wafers, denoted in the following as wafer A and wafer B, have an identical epitaxial layer structure with the same conventional iron doping profile, but different unintentionally incorporated background carbon impurity concentrations in the buffer layer: 4×10^{16}cm^{-3}carbon (A) and $3\pm1\times10^{17}$cm^{-3}carbon (B) (Supplementary Table 1 and Extended Data Fig. 3a). Both exhibit similar DC performance in terms of threshold voltage, saturated current, transconductance as illustrated in Fig. 1c and 1d, and similar excellent RF characteristics of 4W/mm RF output power and ~70% power added efficiency at 1GHz and V_{DS}=28V[32]. However, they show a subtle difference in the electrical performance namely wafer B displays the frequently observed “kink effect”, a threshold voltage instability only present at low source-drain bias, whereas wafer A is almost “kink” free[33] (Fig. 1c and 1d). More detailed device information can be found in Methods.

Fig. 2a and 2b show the EFISHG extracted quantitative electric field distribution around the channel of AlGaN/GaN HEMTs in wafers A and B, respectively, which are surprisingly dramatically different from each other. These are determined from the measured SHG intensity profile shown in Extended Data Fig. 4. The E_x distribution at different source-drain bias voltages is determined from the SHG signal according to equation (2). Reflectance normalization (Extended Data Fig. 4) and integration calibration from source to drain was applied (Extended Data Fig. 5) to give a quantitative measure.

The electric field distribution for wafer A (Fig. 2a) shows an E_x peak on the drain-side gate edge for all source-drain biases, increasing in magnitude as well as increasing in width with rising source-drain bias. The widening electric field distribution is due to the 2DEG depletion region increasing with bias; at about 90V a shoulder forms in the electric field distribution. This is likely due to a combination of the field plating effect of the gate wing and surface charging causing a "virtual gate" extension of the electric field towards the drain. This behaviour is consistent with the standard description of the operation of a GaN HEMT and would be the result of most device simulations. The E_x electric field in this region defines the breakdown voltage of the RF device with iron-doped buffer and directly relates to device degradation processes including current collapse, and gate leakage[1,5,6].

In contrast, wafer B manifests a greatly more complex behaviour. When V_{DS} is below 20V, wafer B shows similar electric field distribution and dependence as wafer A. However above 30V, a different pattern emerges with a saturated peak E_x value at the gate edge and increasing electric field strength within the entire drain access region; another E_x electric field peak starts to appear at the drain edge for the highest source-drain biases.

Discussion and comparison to device simulation

EFISHG has observed a dramatic difference in the electric field distribution in the device channel between wafers A and B despite the basic terminal currents being similar under both RF and DC (Fig. 1c and 1d), i.e., the DC device performance is not a good indicator of the electric field distribution.

GaN HEMTs require a semi-insulating buffer to suppress buffer leakage as a result of short-channel effects[34]. This is normally achieved by the incorporation of a deep acceptor trap into the buffer, and for RF applications, this is usually iron which has its acceptor energy level in the region of 0.5-0.7eV below the conduction band, and which might be expected to result in a n-type buffer. However, GaN for commercial HEMTs is grown using MOCVD which inevitably also incorporates a background density of carbon. This primarily resides substitutionally on the nitrogen site resulting in a deep acceptor, C_N, with energy level 0.9eV above the valence band[35]. If the concentration of C_N is higher than any background intrinsic or extrinsic donor impurities[36] (such as vacancies, oxygen or Si impurities, or carbon substituted on the Ga site), then the Fermi level in the bulk will reside at the C_N level, the iron acceptors will all be neutral, and the buffer will be p-type[1]. Hence small densities of background impurities much lower than the iron density can dramatically change the Fermi level in the bulk and switch the majority carrier from low densities of electrons to small densities of holes. This should result in a major change in the electric field distribution, and an associated reduction in the peak electric field with consequences for device reliability[37]. The low carbon density in wafer A might be expected to result in a highly resistive n-type buffer with the Fermi level pinned close to the Fe trap level, and the higher carbon as in wafer B to switch the buffer to highly resistive p-type isolated from the 2DEG by a p-n diode.

Iron-doped devices with the same structure as wafers A and B have therefore been modelled with the Silvaco Atlas[38] 2D drift-diffusion simulator as described in Methods. The associated net ionized charge is shown in Fig. 3a and 3b at V_{DS}=75V and V_{GS}=-6V, and the simulated E_x component of the electric field in Fig. 3c and 3d. For wafer A, the Fermi level of the buffer is close to Fe trap level (Extended Data Fig. 3b) and the buffer is n-type like the 2DEG, resistively preventing a significant voltage drop occurring between the 2DEG and the buffer and suppressing charging. The only buffer charge forms under the gate, and is exactly as normally expected[1]. However, for wafer B, the Fermi level of buffer is pinned to C_N level making it p-type (Extended Data Fig. 3b) and the buffer is isolated from the 2DEG by a reverse biased p-n junction which extends from gate to drain, allowing a voltage drop of up to 25V between the 2DEG and the buffer to develop, and allowing a depletion charge to be present across the entire gate-drain gap. A preferential leakage across the p-n diode associated with threading dislocations is implemented under the contacts[39-41], providing a path for hole leakage to occur from the drain into the p-type buffer. This reduces the voltage drop under the contacts; without this leakage path, all the voltage would be dropped under the drain and the device would show dramatic current-collapse[1], and not agree with the experimentally measured IV curves. The negative depletion charge under the gate-drain gap pinches-off and suppresses the 2DEG, allowing a lateral E_x field to be present in the entire gap, with a maximum at both gate and drain edges.

Fig. 4a and 4b shows the simulated EFISHG electric field signal determined from Fig. 3c and 3d, when averaging laterally along the device channel, considering the finite lateral spatial resolution of the optical system. For wafer A (Fig. 4a) the result is consistent with the electric field distribution extracted from the EFISHG signal in Fig. 2a, with the electric field largely confined to a 2DEG depletion region at the drain side of the gate. The trend of electric field distribution seen in Fig. 4b captures the behaviour observed for wafer B. The electric field first appears at the gate edge, but at higher V_{DS}, the 2DEG is pinched-off all the way to the drain and allowing a lateral electric field to form in the gate drain gap, before finally becoming concentrated at the drain edge. This observation of full pinch-off in the gate-drain gap and a field peak at the drain edge provides the first direct evidence for a floating p-type buffer in RF devices such as those in wafer B and demonstrates the importance of an independent electric field measurement technique. While a difference in electric field distribution between these two epitaxial wafer variants may be inferred from the occurrence of a small "kink effect"[33] in the IV curve, a clear experimental confirmation was not possible prior to this work.

The EFISHG technique, however, is not only able to record line scans but also capable of electric field mapping. Fig. 2c and 2d shows 2D maps of the E_x distribution using the same extraction method as that in Fig. 2a and 2b. For wafer A, E_x is reasonably uniform across the gate width, whereas for wafer B a significant nonuniformity of E_x electric field distribution is apparent, in particular showing localised electric field peaks directly located under the drain contact. This non-uniform field implies a nonuniform distribution of vertical leakage paths through the p-n junction which results in a local E_x field, presumably associated with specific dislocations or dislocation clusters under the drain, confirming our assumption in the device modelling of local leakage pathways underneath the drain contact. In general, for devices which have a floating p-type buffer the exact details of hole transport through the leakage path, negative charge storage in the buffer and final local E_x field under the drain contact are dependent on the ratio of the leakage path resistances in the depletion region, in the p-type buffer, and under the contacts, which impacts the overall electric field distribution in the devices. TCAD simulation is normally only 2D and does not take account of localised 3D effects such as these localised leakage paths revealed here. Hence simulation cannot capture the exact behaviour of the device; EFISHG is required to determine the true electric field distribution in devices.

Conclusions

We have developed an EFISHG based method that can quantitatively map the in-plane (E_x) electric field in non-centrosymmetric wide bandgap semiconductor devices. The electric field is extracted from the field dependent SHG signal, with illumination and SHG light collection through the backside of the transparent substrate, giving unobscured access to the device channel. Crucially this allows calibration of the electric field strength and thus quantitative measurements. GaN-on-SiC HEMTs were used to illustrate the capabilities of the technique, demonstrating how background dopants influence electric field distribution and device performance. Small changes in buffer doping can dramatically change the electric field distribution with consequences for device reliability, which cannot be directly inferred from DC device performance. The effects of non-uniform distribution of leakage paths have been observed directly from the electric field mapping; these effects cannot be captured from device simulation, illustrating that the EFISHG technique is required to determine the true electric field distribution in GaN devices and its effect on device operation. Our approach is generic and could be applied to other wide bandgap (optically transparent) semiconductor devices, including SiC, Ga_2O_3 and diamond device technology.

Methods

EFISHG setup

Extended Data Fig. 1 illustrates the schematic of the experimental setup for EFISHG and signal acquisition. The laser source used in the experiment for generating SHG response is an ultrafast Ti: sapphire laser (Mai Tai HP), tuneable from 680 to 1080nm; here we used a fundamental beam at 800nm (~100fs, 80MHz, pulse energy ~37nJ). A half waveplate and a Brewster type polarizer are utilized to act as variable attenuator to adjust the polarization state and power level of the probe beam. A short pass dichroic mirror is used to mitigate any parasitic SH light. The 800nm laser beam is focussed by a 50× magnification 0.5 NA objective lens onto the sample with a spot size of approximately 765 nm in a normal-incidence geometry (Extended Data Fig. 2). A 90° mirror cube was mounted to the microscope column, on which the objective lens was mounted; the sample was held 90° to the plane of the stage where XYZ translation with 0.1µm accuracy can be performed. The SH light originating from the sample is then separated from residual fundamental light using a short pass filter before entering an avalanche photodetector. The incident light is linearly polarized, aligned in the direction of the lateral electric field, E_x, in the device from drain to source. A polarizer along the detection path was used to let the SHG light with the same polarization as the incident laser pass through. Since the SHG intensity increases as 2ω approaches the GaN bandgap[42], to maximise efficiency, the laser wavelength was chosen to be 800nm, with 400nm SHG wavelength. This is close to, but below the bandgap absorption edge of the 4H-SiC substrate (375nm) or GaN layer (365 nm). To increase signal to noise ratio in the measurement, for the results in Fig. 2 the laser was chopped at a frequency of 5 kHz, and the avalanche photodetector output is locked to the chopper frequency. Alternatively, the voltage applied to the device can be modulated.

Device information

The epitaxy layer structure of the AlGaN/GaN HEMT is shown in Fig. 1a. Two wafers with different doping concentration in GaN buffer grown by metal-organic chemical vapor deposition (MOCVD) were studied. Both wafers have nominally identical layer structure, Si_3N_4 passivation, AlGaN barrier, unintentionally doped (UID) GaN channel, doped GaN buffer and insulating SiC substrate. Dopant profiles measured by secondary ion mass spectroscopy (SIMS) are shown in

Extended Data Fig. 3a for iron (Fe) and carbon (C). Conventional iron doping was incorporated in the GaN buffer of both wafers to suppress leakage, with doping density decreasing exponentially from the bottom of the buffer towards the device channel. The different growth conditions resulted in different unintentionally incorporated carbon profiles in the bulk with wafer B having a much higher density. Two-finger devices with gate width of 125 µm, gate foot length of 0.25 µm, source-gate gap of 1 µm and gate-drain gap of 4.25 µm were processed, with silicon nitride surface passivation.

Device Simulation

The devices were simulated using the Silvaco Atlas drift-diffusion simulator following the approach used in previous work[33]. The two buffer doping combinations considered in the simulation are shown in Supplementary Table 1, approximating the SIMS profiles (Extended Data Fig. 3a). The compensating donor density is unknown and cannot be measured with SIMS but has been set so that wafer A is n-type and B is p type. The compensation ratio (donor density / carbon on nitrogen site (C_N) density) of wafer B was set to be 0.5, consistent with the compensation ratio seen in power switching devices[43,44] and hydride vapour phase epitaxial GaN. The resulting band diagrams are shown in Extended Data Fig. 3b. These show that for wafer A the Fermi level is close to the iron trap level, the majority carriers are electrons, and there is a resistive contact between the epitaxial bulk and the 2DEG. For wafer B, the Fermi level is pinned to the C_N trap level, the majority carriers in the GaN bulk are holes, and there is a p-n junction isolating the 2DEG from the GaN bulk. Experimentally, it has been demonstrated that vertical leakage paths along threading dislocations through the GaN are often present, representing a band-to-band leakage mechanism[45] that allows a contact between the drain and floating carbon-doped p-type buffer region. Such a leakage path[41,46] was incorporated into the simulation in order to explain the RF and transient transistor behaviour[1], and also to explain the uniform electric field seen in the gate-drain gap for $30V<V_{DS}<90V$ in wafer B shown in this work. Since it is difficult to include band-to-band leakage directly into the simulation, a heavily doped p-type shorting region under drain and source contacts is implemented to provide a path for holes to flow into the p-type GaN buffer[37].

EFISHG signal analysis

EFISHG is a third-order nonlinear optical process, where the strength of the applied electric field in the material system determines the conversion efficiency of two incident photons of frequency ω to a single photon of frequency 2ω, exploiting the third-order nonlinear susceptibility $\chi^{(3)}$ which can be expressed using equation (1). Within the electric-dipole approximation, $P^0_{2\omega}$ stems predominantly from the second-order nonlinear response of the bulk, surface and interface dipole in the device via $\chi^{(2)}_{\mathrm{xzx}}$, although other nonlinear sources including EFISHG induced by the piezoelectric field and built-in polarization field would also contribute. $\chi^{(3)}_{\mathrm{xxxx}}$ determines the electric field induced EFISHG signal, while contribution of $\chi^{(3)}_{\mathrm{xyyx}}$, $\chi^{(3)}_{\mathrm{xzzx}}$ and $\chi^{(3)}_{\mathrm{xxzz}}$ to $P^{\mathrm{EFISHG}}_{2\omega}$ are insignificant compared with that of $\chi^{(3)}_{\mathrm{xxxx}}$, if a moderate numerical aperture (NA) objective lens is used and the optical electric field components are negligible in y and z direction[47] (Fig. 1a). Thus, the electric field measured by EFISHG signal is mainly lateral electric field E_{x}, and the contribution from the vertical electric field E_{z} is negligible. More discussion on this point can be found in the Supplementary Note 2 and Supplementary Fig.1.

The intensity of the measured SHG signal as a function of the power of the incident laser is shown in Supplementary Fig. 2. The solid line represents a least-squares fit of the data points indicating a fit exponent of 1.99. The quadratic dependence of SHG signal on incident laser intensity is consistent with equation (1) confirming the SH nature of the signal. Supplementary Fig. 4 and 5 show SHG intensity $I_{2\omega}$ at different positions between gate and drain contacts as a function of gate-drain voltage V_{DG} applied. The solid curves represent fits of Supplementary equation (4) to the data within V_{DG} ranges where E_{x} is linear to V_{DG} (Supplementary Fig. 3). For devices on both wafers, cross term in Supplementary equation (4) is absent at all positions between gate and drain contact. In previous EFISHG works in centrosymmetric materials[48,15], the dependence of $I_{2\omega}$ on applied field is either quasi-linear or quadratic and E_{x} can be extracted from $I_{2\omega}$ or $\sqrt{I_{2\omega}}$. However, for GaN HEMTs, E_{x} measurement requires the cross term to be determined from the dependence of $I_{2\omega}$ on applied field, using the fitting method described in Supplementary Note 3. The cross term for the devices measured here is zero, resulting in the electric field dependence equation (2).

The pump beam is focused through the SiC substrate; the SiC/GaN interface has a negligible reflectivity due to the similar indices of refraction (refractive index n_{SiC}=2.8 versus n_{GaN}=2.6 at 400nm). SHG light is collected after being reflected from the source, drain and gate contacts or the passivation/air interface. A reference laser beam at the same wavelength as the SH signal is used to calibrate the light reflection efficiency at each point, to take into account the changes in reflectivity across the device channel. The measured reflectance from source to drain in the two wafers is shown in Extended Data Fig. 4. A bare SiC wafer with known reflectance (SiC/air = 0.21 at 400nm) was used as calibration.

After the reflectance calibration, the electric field (E_x) distribution from source to drain is extracted from the SHG signal profiles shown in Extended Data Fig. 4. However, quantitative determination of E_x requires the value of the proportionality factor α in equation (2). This is constrained by integration of E_x over the length of channel to be consistent with the gate-drain bias. The potential difference between source and drain obtained by integrating E_x over the length of channel at different biases is shown in Extended Data Fig. 5. For wafer A, the potential difference (Extended Data Fig. 5a) increases linearly with applied gate-drain voltage, and a proportionality factor of α=2.1 in equation (2) was determined. The potential difference in wafer B is only linear for gate-drain biases up to 111V (Extended Data Fig. 5b) and we determined α=3.4. The somewhat reduced value obtained for the highest voltage is due to the extension of the electric field underneath the drain contact under high gate-drain voltages related to leakage paths (Supplementary Fig. 6). The linear dependence of potential difference on gate-drain bias in Extended Data Fig. 5 demonstrates the validity of the electric field extraction and calibration method. The difference of proportionality factors reflects differences in the beam path of the optical setup in the measurement of the two wafers. Any light attenuation in the beam path will affect the proportionality factor in equation (2), including reflectivity from the back of the wafer, reflectivity of interfaces inside the epitaxial and device structure, absorbance within the wafer, alignment of the optical setup, etc. These sources can be different from wafer to wafer; it is important to determine this calibration factor for each sample.

A lock-in detection was implemented, with the output signal of the avalanche photodetector measuring the SHG signal locked to the laser chopper frequency in the lock-in amplifier, with the device biased under DC voltage. This was used for both line scans and 2D mapping (Fig. 2). Alternatively, the voltage applied to the device can be modulated instead of the laser, with an example result illustrated in Supplementary Fig. 7. Then, the fundamental SHG signal $\left|P_{2\omega}^{0}\right|^2$ in equation (1) is suppressed and the output SHG signal contains purely the electric-field dependent signal $\left|P_{2\omega}^{\mathrm{EFISHG}}\right|^2+\left|2P_{2\omega}^{0}P_{2\omega}^{\mathrm{EFISHG}}\right|$ after applying the reflectivity correction. However, to achieve good signal-to-noise ratio a rather large modulating voltage had to be applied, here (75 ± 75) V, which makes it challenging to assign the electric field determined to a specific voltage, though it allows for faster mapping of electric field distribution across large device areas. In all cases, the SHG signal collected is the moving average of signals over 2 seconds detected by photodetector and lock-in amplifier when the standard deviation (SD) is below 1.5 μV. The error bar representing this SD is usually invisible and has been eliminated in all figures.

Data availability

The data that support the plots within this paper and other finding of this study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability

The custom-developed codes for the Silvaco Atlas simulation, LabView data acquisition and MATLAB data analysis is available from the corresponding author upon reasonable request.

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Author contributions

J. W. P and M. K conceived the idea for the project. Y. C designed the EFISHG setup and experiment procedure, conducted the experiments and analysed the results. J. W. P provided important expertise on the technique aspects. F. Y conducted the simulation. M. J. U provided significant input on the interpretation of data. All authors participated in the scientific discussion. Y. C wrote the manuscript with the assistance of J. W. P, M. J. U, and M. K. M. K supervised the project.

Competing interests

The authors declare no competing interests.

Figure legends

Fig. 1 Schematic of EFISHG experiment on GaN HEMT and device information. a, Schematic of GaN-on-SiC HEMT, showing device structure and laser focused on device, and EFISHG signal generated. The incident laser is largely with k-vector in the z-axis direction and is polarized in x-axis direction. The SHG signal is collected after reflection and can be polarization analysed. **b**, SEM image of the two-finger device studied, and optical image captured from the backside of the wafer. The length of scale bars in SEM and optical images are 50 and 20 µm, respectively. **c**, **d**, DC I_{DS}-V_{DS} sweeps for devices on wafer A and wafer B, respectively; V_{GS} is stepped from −3 to 0 V in steps of 0.5 V.

Fig. 2 Electric field distribution in GaN HEMT devices. a, **b**, Electric field profiles from the source to drain contact for devices on wafer A and wafer B, respectively, extracted from the EFISHG measurement; the laser beam was modulated at 5 kHz. Devices were operated in the OFF state (V_{GS}=-6V) at different source-drain voltages V_{DS}. **c**, **d**, 2D maps of the electric field for devices on wafer A and wafer B, respectively, at V_{GS}= -6V, and V_{DS} = 120V.

Fig. 3 Simulation results for devices on wafer A and B. a, **b**, Net ionized charge density in OFF state (V_{GS}=-6V, V_{DS}=75V), for devices on wafer A and wafer B, respectively. **c**, **d**, Simulated in-plane electric field E_x contour of devices on wafer A and wafer B, respectively.

Fig. 4 Simulated channel in-plane electric field E_x averaged over the lateral spatial resolution of the EFISHG measurement. a, **b**, Electric field E_x under OFF state (V_{GS}=-6V) at different source-drain voltages V_{DS} for devices on wafer A and wafer B, respectively.