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Enhancing the intrinsic p-type conductivity of the ultra-wide bandgap Ga₂O₃ semiconductor

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While there are several n-type transparent semiconductor oxides (TSO) for optoelectronic applications (e.g. LEDs, solar cells or display TFTs), their required p-type counterpart oxides are known to be more challenging. At this time, the n-type TSO with the largest bandgap (~ 5 eV) is Ga₂O₃ that holds the promise of extending the light transparency further into the deep ultraviolet. In this work, it is demonstrated that strongly compensated Ga₂O₃ is also an intrinsic (or native) p-type TSO with the largest bandgap for any reported p-type TSO (e.g. NiO, SnO, delafossites, oxychalcogenides). The achievement of hole mobility in excess of $10 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and (high temperature) free hole concentrations in the $\sim 10^{17} \text{ cm}^{-3}$ range challenges the current thinking about achieving p-type conductivity in Ga₂O₃ being "out of the question". The results presented in this paper therefore further clarify that p-type Ga₂O₃ is possible, although more research must be conducted to determine what are the real prospects for Ga₂O₃ solar blind bipolar optoelectronics and ultra-high power electronics based on p–n homojunctions.

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Introduction

Recently, ultra-wide band gap gallium oxide (Ga₂O₃) has been receiving a lot of renewed attention as a transparent semi-conducting oxide (TSO) champion owing to its unusual material properties^{1–3} large tuneable conductivity,^{4,5} extremely high breakdown field,^{6–8} unique optoelectronic properties^{9–11} and low cost.¹² TSOs are a class of key enabling materials in increasingly high demand because of the immediate applications they can find in a variety of new technologies, ranging from thin-film coatings and sensor devices, to transparent electronics and optoelectronics in telecommunications.^{13,14} Some TSOs are indeed the standard choice for use in transparent electrode applications¹⁵ and are also hugely important for information and communication technologies such as displays, touch screens, solar cells or light emitting diodes.¹³ Another key factor in the adoption of oxide semiconductors is that they are compatible with the strict

manufacturing requirements of large-scale, large-volume, flexible, low cost and disposable/reusable devices.^{16,17} The arising TSO technology based on ultra-wide bandgap gallium oxide (~ 4.8 eV) holds the promise of extending many optoelectronic applications further into the deep ultraviolet range, surpassing the conventional wide bandgap near ultraviolet limit (~ 3.5 eV) of TSOs (e.g. ZnO, SnO₂ or In₂O₃).

However, to exploit the full potential of any emerging ultra-wide bandgap transparent optoelectronic technology, both n- and p-type conductivity (*i.e.* bipolarity), should be attained. Intrinsic wide bandgap transparent semiconductor oxides are predominately n-type due to their ability to form oxygen vacancies.¹⁸ Depositing or annealing in reduced oxygen partial pressure can increase the conductivity of the oxide by introducing more carriers. In contrast, there are few predominantly p-type oxide semiconductors due to cation vacancies, and examples include Cu₂O, SnO or NiO.^{19,20} The majority of oxides have fundamental thermodynamic constraints, making their p-type doping difficult. More specifically, the formation of compensating intrinsic defects when lowering the Fermi energy towards the valence band has been identified as a main impediment to p-type doping in many oxides.²¹ In any case, oxides generally exhibit an important doping asymmetry and bipolar oxide semiconductors²² represent only a small subset (e.g. CuInO₂,²³ SnO,²⁴ Ni_xCd_{1–x}O_{1+δ},²⁵ SnNb₂O₆,²⁶ ZrOS²⁷). Bipolar electronic features are also extremely interesting for Ga₂O₃ ultra-wide bandgap power electronics to define the main blocking p–n junctions.^{28,29}

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Here, we provide stronger experimental evidence supporting our previous report³⁰ underlying that Ga₂O₃ is a p-type native (or intrinsic) semiconductor. In addition, we report a route for the enhancement of the native p-type conductivity in undoped Ga₂O₃ by annealing in an oxygen atmosphere. While high n-type conductivity in β-Ga₂O₃ can be efficiently achieved by impurity doping with Sn, Si, Ge, F or Cl^{31,32} (and even metallic conductivity due to charge accumulation on the surface in undoped β-Ga₂O₃^{3,33}), p-type conductivity is still controversial. Remarkably we corroborate that, thanks to the β-Ga₂O₃ particular point defect chemistry and the large formation energy of oxygen vacancies⁵ (the native donor which can play the role of compensators for holes), it is possible to achieve the realization of a p-type conductivity even in undoped layers.³⁰

Results and discussion

Thermodynamic analyses

Thermodynamic analyses of point defects and charge carriers have been carried out to determine the best conditions for growing highly compensated p-type β-Ga₂O₃ thin-films. By using the Kröger method of quasi-chemical equations,³⁴ the thermodynamic equilibrium in the β-Ga₂O₃ (crystal)–O₂ (gas) system was established to define the dependence of point defects and charge carriers on temperature (*T*) and oxygen partial pressure (*P*_{hole}). In general, high oxygen pressures are required to achieve p-type conductivity triggered by native (or intrinsic) acceptors, which are associated to gallium vacancies (*V*_{Ga}). The thermodynamic analysis shows that high oxygen pressures guarantee the appearance of uncompensated hole conductivity effectively suppressing the compensation by native donors, which are associated primarily to oxygen vacancies (*V*_O).

The growth conditions (oxygen partial pressure and temperature) in which acceptors become dominant species, (*i.e.*, the compensating donor defects are suppressed), can be determined by means of the following expression:

$$P_{\text{hole}} = \frac{K_S^{2/3} K_D^2}{K_i^2 K_V^{2/3}} \quad (1)$$

where *K*_S, *K*_D, *K*_i and *K*_V are the reaction constants of creation of a Schottky pair, ionization of native donor, lattice thermal ionization and creation of oxygen vacancy, respectively. Details about the method have been reported in ref. 30. As shown in the map of Fig. 1(a), the pressure required for intrinsic p-type conductivity increases sharply with *T*. If the growth conditions are located in the upper part of the map, rather uncompensated Ga₂O₃ (*i.e.*, low p-type conductivity) should be expected, whereas if growth conditions are located in the lower part, highly compensated samples should be obtained (higher p-type conductivity). Wang and co-authors have suggested also that high temperature and high oxygen partial pressure are in favor of p-type doping in β-Ga₂O₃ crystals by weakening the self-compensation effect.³⁵

Therefore, to achieve larger intrinsic p-type conductivities, strongly compensated β-Ga₂O₃ layers should be grown, as is demonstrated by metal–organic chemical vapour deposition

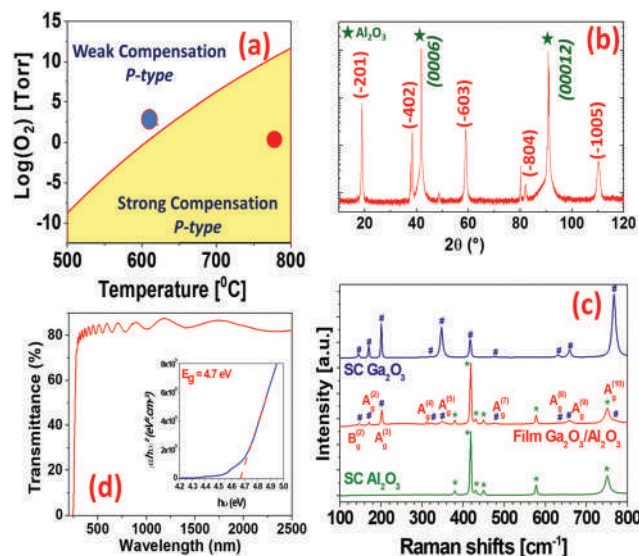


Fig. 1 (a) The dependence of growth pressure when hole conductivity appears on growth temperature. The red point corresponds to our growth conditions, while the blue point corresponds to post annealing conditions (*T* = 600 °C, pressure = 1 atm). (b) The X-ray diffractogram of a β-Ga₂O₃ film grown on (0001) sapphire (intensity in log scale); the peaks labelled by "*" indicate XRD reflections corresponding to the sapphire substrate. (c) Raman spectra recorded using 514.5 nm excitation for: red trace: (−201) β-Ga₂O₃ thin film grown on c-cut sapphire substrates; green trace: blank c-cut sapphire; blue trace: (100) β-Ga₂O₃ single crystal. The phonon modes for β-Ga₂O₃ are labeled using "#" while the phonon modes for α-Al₂O₃ substrate are labeled using "*". (d) Optical transmission spectrum *T* [%] in the 200–2500 nm range of photon wavelength. Inset: optical band gap as determined from a classical Tauc plot extrapolation.

(MOCVD) on sapphire substrates. Growth details are given in the Experimental details section. It is worth mentioning that the Ga₂O₃ p-type conductivity has been consistently measured in eight different samples (under varying growth conditions) but, in the following, the discussion is restricted for simplicity to the most illustrative one.

Sample preparation and physical properties

β-Ga₂O₃ high quality thin films have already been grown by MOCVD using commercial metal–organic precursors such as trimethylgallium (TMGa), and pure oxygen.^{36–39} MOCVD is an industrial technique which allows the growth of large-area, uniform semiconductor layers (*e.g.* III–V compounds) with excellent control of the purity. In the case of β-Ga₂O₃, we thus expect high resistivity of the grown material due to a very low concentration of impurities. In agreement with that point, Almena *et al.*³⁶ observed highly resistive electrical properties as no measurable conductivity was observed by Hall measurements, and Sbrokey *et al.*⁴⁰ reported insulating films with sheet resistivity >10¹⁰ Ω □^{−1}, beyond the measurement range of their four-probe equipment. Herein, a strongly compensated undoped β-Ga₂O₃ layer (~500 nm-thick) was grown (see Experimental section) on c-sapphire substrates at *T* = 775 °C and *p*_{O₂} = 5 Torr (red dot in Fig. 1(a)). X-Ray Cu-Kα diffractograms, recorded between 2θ = 10 and 130°, in θ/2θ configuration,

exhibit a highly textured film of gallium oxide in the β -Ga₂O₃ phase with monoclinic space group ($C2/m$) symmetry (Fig. 1(b)). More intense peaks correspond to (0, 0, 0, 6) and (0, 0, 0, 12) Bragg reflections of the c-Al₂O₃ substrates (with also tiny peaks at $2\theta = 37.61^\circ$ and 80.13° associated to Cu-K β radiation). The more intense Bragg peaks of the film, at 2θ values of 18.91, 38.33, 58.98, 82.01 and 110.21° , correspond to the family $(-2n, 0, n)$ planes. Their indexes in $C2/m$ space group are (-201) , (-402) , (-603) , (-804) , (-1005) , respectively, with a reticular distance $d(-2,0,1) = 0.4690$ nm, and intensity ratio in agreement with previous works for β -Ga₂O₃ films grown on c-sapphire.^{41–44} The only additional detected Bragg peak at 2θ value of 48.71° might be indexed with (5 0 1) β -Ga₂O₃, with an intensity ratio lower than 0.5%, and may be negligible in terms of crystallized volume. So we concluded that studied thin films are a textured $(-2\ 0\ 1)$ β -Ga₂O₃ crystalline phase. The film crystalline quality has also been analysed by Raman spectroscopy. Fig. 1(c) show Raman spectra recorded using 514.5 nm excitation for: (red curve) (-201) textured β -Ga₂O₃ thin film grown on c-cut sapphire substrates; (green curve) a blank c-cut sapphire (0001) α -Al₂O₃; and (blue curve), a (100)-cut β -Ga₂O₃ single crystal. The primitive unit cell of β -Ga₂O₃ consists of 10 atoms which results in 30 phonon modes; of which 27 are optical modes. At the Γ -point, these belong to the irreducible representation.⁴⁵

$$\Gamma^{\text{Opt}} = 10A_g + 5B_g + 4A_u + 8B_u \quad (2)$$

The modes with A_g and B_g symmetry are Raman active, while those with odd parity (index u) are infrared active. The Raman spectrum for the (-201) textured β -Ga₂O₃ thin film grown on c-cut sapphire substrates is a combination of β -Ga₂O₃ (labelled using “#” in Fig. 1(c)) and α -Al₂O₃ phonon modes (labelled using “*” in Fig. 1(c)). No Raman phonon modes belonging to other Ga₂O₃ polymorphs have been detected, thus demonstrating that we have a single β -Ga₂O₃ phase. The Ga₂O₃ thin film Raman phonon modes full width at half maximum (FWHM) of the β -Ga₂O₃ is close to that of single crystal β -Ga₂O₃ and this is indicative for a very good crystallinity. Fig. 1(d) shows the transmission spectrum T [%] in the 200–2500 nm range. The Ga₂O₃ thin films are highly transparent, with $T \sim 80\%$ in UV-VIS-NIR. The optical band gap is determined as $E_g = 4.7 \pm 0.1$ eV, from classical Tauc plot extrapolation (see the inset in Fig. 1(d)), which is also in agreement with previous reports.³⁰

Electrical properties

Here, a detailed study of the electrical transport properties of strongly compensated β -Ga₂O₃ has been performed thanks to use of a home developed in GEMaC laboratory high temperature and high impedance set-up. Van der Pauw Hall effect measurements were employed to determine the resistivity, carrier type, density and mobility. I - V characteristics for ohmic contacts at 700 K is shown in the inset of Fig. 2(a). Resistivity at $T = 530$ K (the lowest temperature for valid measurements) was found to be $\rho = 2.9 \times 10^5 \Omega \text{ cm}$. By heating the sample up to

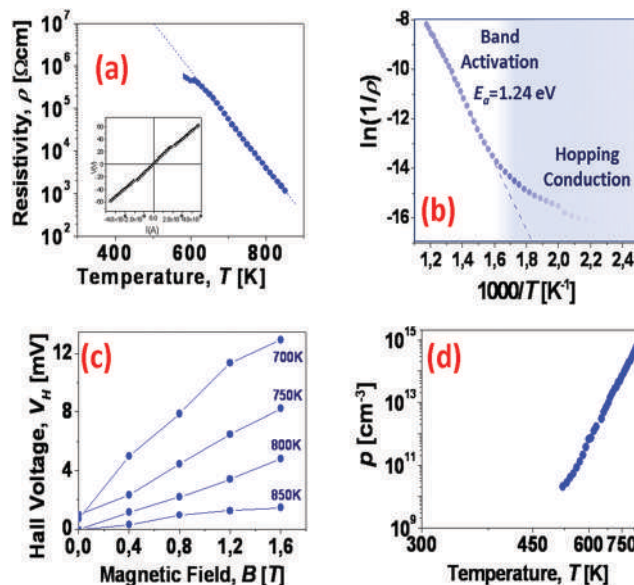


Fig. 2 (a) Resistivity vs. temperature change for β -Ga₂O₃ thin films, in the range from 530–850 K; inset: I - V characteristics of two-point contact measurements at 700 K. (b) $\ln(\sigma)$ vs. T dependence: two regimes of conductivity are seen, band activation above $T > 625$ K and at lower temperatures when hopping conduction starts to be more important. Activation energy of conductivity is estimated as $E_a = 1.24$ eV. (c) Hall voltage vs. magnetic field at different temperatures. (d) Temperature dependence for Hall hole concentration.

$T = 850$ K, the resistivity decreases down to $\rho = 1.2 \times 10^3 \Omega \text{ cm}$ as shown in Fig. 2(a). The resistivity dependence on T , $\rho(T)$, shows the typical behaviour of a semi-insulating material, with a hopping conductivity enhancement above 650 K (see Fig. 2(b)). The determination of the majority carrier type is not trivial in practice when the sample is of high resistance ($> 10^7 \Omega$) due to the difficulty in correctly extracting the Hall voltage (V_H) from the total measured voltage. To further validate the sign of majority carriers, the Hall voltage dependence on the applied magnetic field was measured at different temperatures. Hall voltage measurements were carried out at varying magnetic fields (0–1.6 T) in the temperature range of 650–850 K. In a non-magnetic material, V_H is linearly proportional to the applied magnetic field and a positive sign indicates that the majority charge carriers are p-type (holes). As shown in Fig. 2(c), the positive V_H linearly increase with perpendicularly applied magnetic field. This confirms that the layer was p-type. The temperature dependence for Hall hole concentration is shown in Fig. 2(d). At the largest available temperature of 850 K, the free hole concentration is $p = 5.6 \times 10^{14} \text{ cm}^{-3}$. Hall hole mobilities vary between $\mu = 9.6$ – $8.0 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in 680–850 K temperature range.

A carrier activation energy of $E_a = 1.24 \pm 0.05$ eV has been determined from the $\ln(p)$ vs. $1/T$ plot. For a p-type semiconductor, the general description of the hole concentration at a temperature T (K) is given by the neutrality equation:

$$\frac{g_d p (N_D + p)}{M_V (N_A - N_D - p)} = \exp\left(-\frac{E_i}{kT}\right) \quad (3)$$

where k is Boltzmann's constant ($\text{m}^2 \text{kg s}^{-2} \text{K}^{-1}$), g_D is the acceptor degeneracy, N_A is the acceptor concentration (cm^{-3}) and N_D is the compensating donor concentration (cm^{-3}). M_V is the hole density of states in the valence band. If $p \ll N_A - N_D$ and $p \ll N_D$, in the strong compensation regime, the neutrality equation (3) becomes:

$$p = \left(\frac{N_A - N_D}{N_D} \right) \left[\frac{M_V}{g_D} \right] \exp \left(-\frac{E_i}{kT} \right) \quad (4)$$

Thus, the experimental activation energy of $E_a = E_i = 1.24 \text{ eV}$ should correspond to the ionization energy of the acceptor centre (E_i). This ionization energy value agrees well with two-times the activation energy estimated (0.56 eV) for a previously reported arguably p-type weakly compensated Ga_2O_3 thin film grown by pulsed laser deposition (PLD).³⁰ A gallium vacancy acceptor level V_{Ga} located at $\sim 1.2 \text{ eV}$ above the valence band has been already reported by several groups by deep-level transient spectroscopy (DLTS).^{46,47}

Oxygen annealing

Annealing in an oxygen rich (*i.e.* Ga deficient) atmosphere should lead to an increase of acceptor V_{Ga} centres. As with many other metal oxides, gallium oxide is a well-known material for gas sensing⁴⁸ and, therefore, the effect of oxygen annealing at high temperatures on the conductivity of insulating bulk $\beta\text{-Ga}_2\text{O}_3$ has been intensively investigated previously.^{49,50} For $\beta\text{-Ga}_2\text{O}_3$, a conductivity activation temperature onset of around $\sim 700^\circ\text{C}$ has been reported. Annealing above 700°C in air or oxygen ambient conditions would lead to the creation of oxygen vacancies (V_{O}) due to the out-diffusion of oxygen atoms from the Ga_2O_3 lattice. This generation of V_{O} leads to an additional source of free-electrons and to a n-type conductivity enhancement. The ionization energy of V_{O} in the case of ceramic $\beta\text{-Ga}_2\text{O}_3$ samples has been estimated to be $\sim 1.5 \text{ eV}$ from the conduction band.⁵¹ The effect of oxygen annealing leading to a decrease of background n-type carrier concentrations for diodes annealed in O_2 ambient and for annealed substrate have been demonstrated.^{33,52–54} Therefore, to enhance hole conductivity while not creating additional oxygen vacancies, post-annealing in pure oxygen atmosphere at a reduced temperature of 600°C has been carried out in a condition of weak compensation (blue spot in Fig. 1(a)). It is worth mentioning that, after annealing, neither X-ray diffractograms nor Raman spectroscopy evidenced any change so that the gallium oxide films would remain structurally unaffected. Electrical transport measurements showed that oxygen annealing leads to a decrease of resistivity from $\rho = 1.2 \times 10^3$ to $1.7 \times 10^2 \Omega \text{ cm}$ at $T = 850 \text{ K}$ while, at room temperature, the resistivity was determined to be $\rho = 1 \times 10^4 \Omega \text{ cm}$ (Fig. 3(a)). We have not detected any “electrical inhomogeneity” performing I - V characterization and resistivity measurements, which could be observed in the case of surface conductivity resulting from a bi-layered structure. A double-slope conductivity curve with two different activation energies has been determined with (high temperature) $E_{a1} = 0.56 \text{ eV}$ and (low temperature) $E_{a2} = 0.17 \text{ eV}$ (Fig. 3(b)). In the high temperature range, the activation energy ($E_{a1} = 0.56 \text{ eV}$) is similar to the half of the activation energy

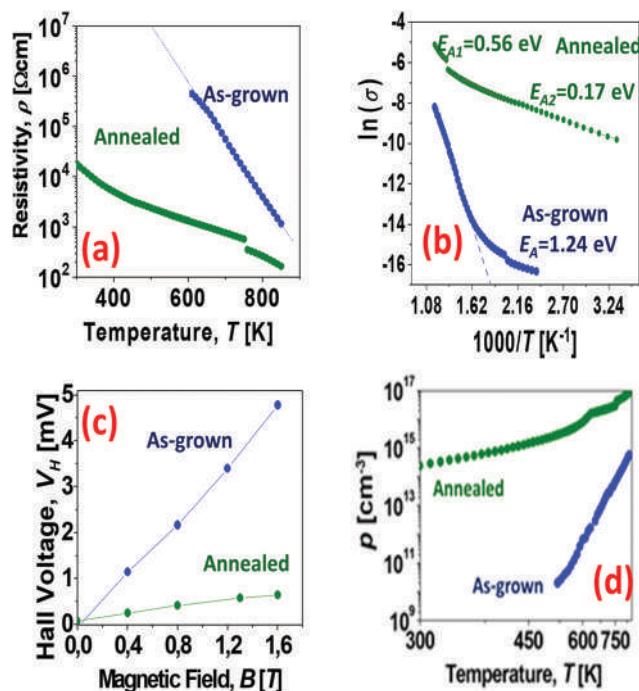


Fig. 3 (a) Resistivity temperature dependence; (b) conductivity $\sigma = 1/\rho$ in \ln -scale vs. $1000/T$ dependence; (c) Hall voltage V_H vs. applied external magnetic field at $T = 850 \text{ K}$; (d) Hall hole concentrations vs. temperature for as-grown and annealed in O_2 at 600°C $\beta\text{-Ga}_2\text{O}_3$ thin films.

of the same acceptor centre but in highly compensated conditions ($E_i = 1.24 \text{ eV}$). The low temperature activation energy (E_{a2}) might be related with another shallow acceptor centre created after annealing in the oxygen atmosphere.

As in the as-grown samples, Hall effect measurement methodology (measuring Hall voltage with different applied magnetic field) was applied for the annealed sample, showing that the annealed sample is p-type as well (see Fig. 3(c)). In this case, the Hall hole concentration was significantly increased up to $p = 5.6 \times 10^{17} \text{ cm}^{-3}$ ($T = 850 \text{ K}$), when compared with available free-hole concentration before annealing ($p = 5.6 \times 10^{14} \text{ cm}^{-3}$). Nevertheless, the Hall mobility is lower, $\mu = 0.4 \text{ cm}^2 \text{ V s}^{-1}$ ($\mu \sim 8.0 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ before annealing), probably due to an increased number of scattering centers. It should be mentioned that to measure the Hall effect over the entire temperature range was complicated owing to this low mobility. Though actually being measured in a narrower temperature range, it appears that the hole mobility does not change significantly with temperature. Therefore, it is concluded that the conductivity activation energy is mainly determined by the activation of free carriers with temperature (Fig. 3(d)). Therefore, we could assume that the conductivity activation energy of $E_{a2} = 0.17 \text{ eV}$ is the acceptor level energy with an ionization energy of around this value.

A potential origin of this shallow level may be further elucidated by considering several theoretical assumptions. It is well-known that, close to stoichiometry, oxide oxygen vacancies tend to be preferentially in a double charged (V_{O}^{++}) state rather than as a single charge (V_{O}^+) state.⁵⁵ In off-stoichiometry states, when hole concentration are important, the compensating

donor defects are expected to be even more abundant in double charged states. Taking this fact into account, we attribute the shallower acceptor centre with $E_{a_2} = 0.17$ eV activation energy to be due to the creation of $V_{Ga}^- - V_O^{++}$ complexes. Indeed, the high probability of creation of such vacancy complexes has been studied in detail by Ingebrigtsen *et al.*⁵⁶ In the case of oxygen annealed strongly compensated β -Ga₂O₃, because of the Coulombic interactions between V_{Ga}^- and V_O^{++} , the V_O^{++} donor centre has a tendency to be located in the vicinity of charged acceptor centre, forming $V_{Ga}^- - V_O^{++}$ complexes. Consequently, the energy of electron localized on V_{Ga}' decreased by amount of $\Delta E = 2e^2/\epsilon R_{As}$, where R_{As} is distance between V_{Ga}^- and V_O^{++} , and ϵ is the static dielectric constant of Ga₂O₃. If V_O^{++} defects are located in the first coordination sphere, their proximity can reduce the electronic level of V_{Ga}^- (1.24 eV) by ~ 1 eV, which is in good agreement with $E_{a_2} = 0.17$ eV activation energy observed in experiment.

Chemical analysis: XPS p-type valence band

X-Ray photoelectron spectroscopy (XPS) is an excellent chemical method to investigate a material's valence band characteristics and brings additional evidence of the presence of states within the bandgap^{57–59} When used in high resolution in the valence band vicinity (*i.e.*, for the lowest binding energies), it is possible to directly detect whether there are states in the lower part of the bandgap (those responsible for p-type character).⁶⁰

As shown in Fig. 4, there was found to be a clear correlation within the amount of states in the lower half of the bandgap and the p-type character in the sequence: n-type (Si-doped) commercial reference, p-type (undoped) and p-type (annealed). The n-type control sample is a commercial (Novel Crystal Technology, Inc.) nominally n-type Si-doped β -Ga₂O₃ ($N_D - N_A = 1.3 \times 10^{18} \text{ cm}^{-3}$) epitaxy (500 nm) grown on a single crystal β -Ga₂O₃ (labelled “n-type (Si-doped)”). For our samples, the valence band edge is shifted towards more p-type using the Ga 3d peak as the calibration peak (lower Fermi level implies more p-type character), see Fig. 4(a) and (b). The numerical values of the energy levels are in agreement with those given by Hall measurements. A zoom of the smallest binding energies further reveals the presence of states within the band gap (Fig. 4(c)–(e)). The counts per second (counts s^{−1}) are normalized to the maximum value in the range of 0–6 eV. The Fermi level is near the conduction band in the case of the commercial Si-doped Ga₂O₃ reference (~ 4.4 eV). For the Ga₂O₃ reference, there is no indication of further tail states within the band gap. The Fermi level is shifted towards an intrinsic value (*i.e.*, mid-gap) in our undoped as-grown Ga₂O₃, but a number of tail states arise at ~ 1.5 – 1.2 eV from the conduction band. In the annealed sample, the states further extend towards the lower part of the bandgap and hence, indicate a much larger p-type carrier density (and hence, conductivity), as the *I*–*V* and Hall experiments suggest. From the extrapolation of the valence band edge, the Fermi level is as low as ~ 0.2 eV for the annealed sample.

Comparison with state-of-the-art

For the majority of oxides, to achieve sizable p-type conductivity is challenging because their valence band maximum consists of

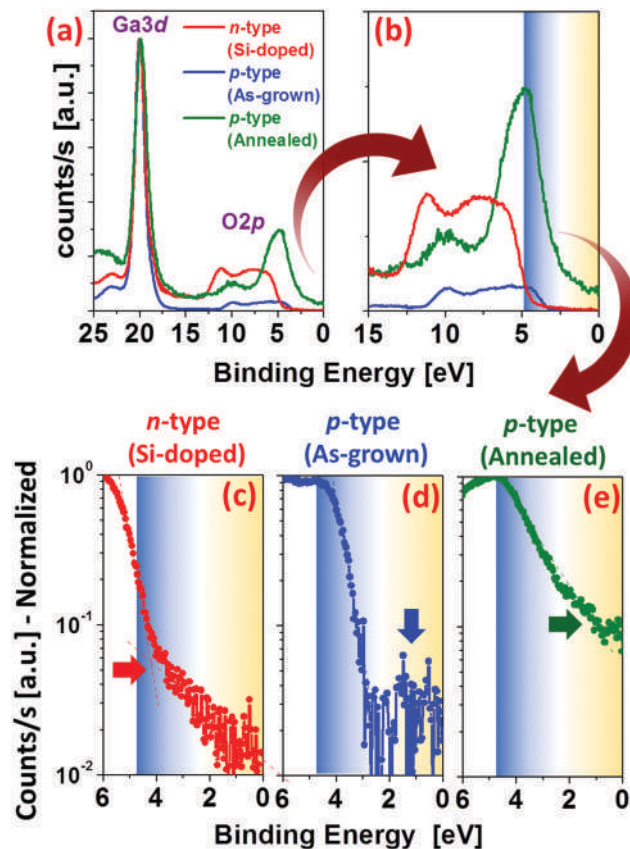


Fig. 4 (a) X-Ray photoelectron spectroscopy of the Ga₂O₃ valence band for a commercial Si-doped (n-type) reference and the p-type as-grown/annealed samples of this work (calibrated with respect to Ga 3d). (b) A zoom of the valence band region, which in the case of stoichiometric Ga₂O₃, has a O 2p character. Investigation of the valence band tail states for (c) n-type (Si-doped), (d) p-type (as-grown) and (e) p-type (annealed) evidencing the presence of states in the lower part of the bandgap.

strongly localized O 2p-derived orbitals. In other words, the valence band of most oxides is rather flat, resulting in deep acceptor levels (lower free hole concentration at room temperature) and larger hole effective masses (lower mobilities).^{61,62} For many years, the possibility of doping p-type Ga₂O₃ has been considered “out of the question” due to the particular flatness of the computed valence band resulting in a high hole effective mass (see *e.g.* ref. 63). A Ga₂O₃ valence band being governed by O 2p orbitals with arguably very low hole mobility and having very small dispersion in the wave vector-energy space has been routinely reported.^{5,64–66} In addition, a strong localization of holes at specific sites in bulk Ga₂O₃ by a self-trapping effect, has also been predicted by first-principles calculations.⁶⁷

Nevertheless, it has been also recently reported that the hole conduction mass in Ga₂O₃ is, indeed, fairly anisotropic and can be as low as $\sim 0.4m_0$ for certain orientations (while larger than $10m_0$ in others)⁶⁸, Fig. 5(a) and (b). Thus, challenging current thinking, we have found experimentally a sizable hole mobility of at least $\sim 10 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ together with an outstanding transparency in the visible region of above 80%. What is more important is the significant “shift of the native p-type conductivity”

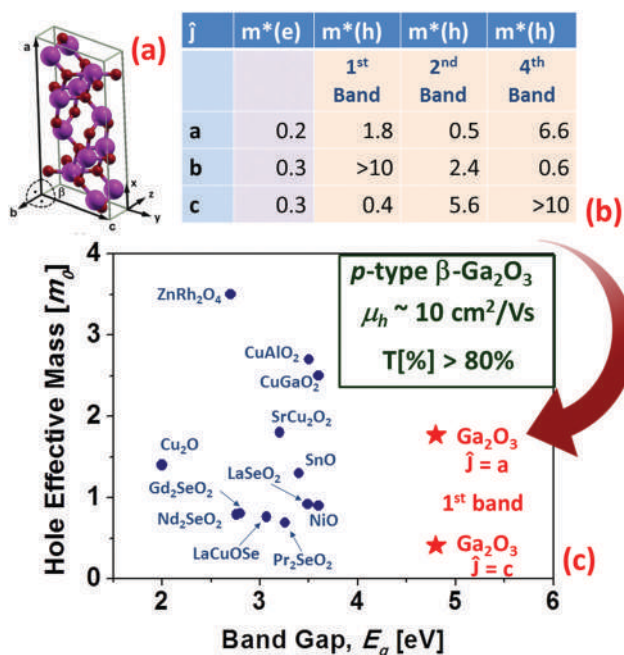


Fig. 5 (a) Unit cell of β -Ga₂O₃ detailing crystallographic coordinate systems. (b) β -Ga₂O₃ effective mass parameters for conduction and valence bands as indexed for lowest transition along directions *a*, *b* and *c* (in units of m_0). (c) Comparison of the predicted effective mass of the ultra-wide bandgap β -Ga₂O₃ compared with other wide-bandgap oxides.^{61,62,69–71} (a) and (b) here are reproduced or adapted with permission from Mock *et al.*, Band-to-band transitions, selection rules, effective mass, and excitonic contributions in monoclinic β -Ga₂O₃, *Phys. Rev. B*, 2017, **96**, 245205 (ref. 68) ©2017 American Physical Society.

up to the ~ 5 eV region (~ 250 nm) when compared with previous p-type conductive oxides such as NiO, SnO, Cu-based delafossites (CuAlO₂, CuGaO₂, SrCu₂O₂) or oxychalcogenides, all of them lying in the range of ~ 2.5 – 3.7 eV,^{61,62,69–71} as shown in Fig. 5(c).

Conclusions

In this work, we corroborate, *via* electrical Hall effect and chemical XPS measurements, that the ultra-wide band gap Ga₂O₃ oxide is a “native” p-type semiconductor oxide even in the case of strong compensation by donor defects. This unusual native p-type nature is due to the Ga₂O₃ particular point defects chemistry, mainly the large formation energy of oxygen donor vacancies, allowing the realization of a p-type nature. This confirms, in practice, that Ga₂O₃ is a p-type TSO with the largest band gap and also is potentially bipolar. The corroboration of this fact might have deep implications in optoelectronics, thanks to the shifting the optical band gap onset, and in power electronics in regard of the device’s breakdown voltage range. Notably, the p-type nature was determined in samples grown by MOCVD, differently to the only previously reported native p-type conductivity for samples grown by PLD.³⁰ Such reproducibility reinforces our claim of possible realization of native hole conductivity in gallium oxide. Annealing in oxygen results in much improved (three-orders of magnitude) free hole

concentration $p(\text{Ox-anneal}) = 5.6 \times 10^{17} \text{ cm}^{-3}$ vs. $p(\text{as-grown}) = 5.6 \times 10^{14} \text{ cm}^{-3}$ ($T = 850 \text{ K}$) and resistivity $\rho(\text{Ox-anneal}) = 1.7 \Omega \text{ cm}$ vs. $\rho(\text{as-grown}) = \rho = 1.2 \times 10^3 \Omega \text{ cm}$ ($T = 850 \text{ K}$). However, the mobility $\mu = 0.4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ($\mu \sim 8.0 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ before annealing) is reduced probably due to a greater number of acceptor scattering centres. The origin of such improved p-type conductivity is preliminarily ascribed to the formation of $V_{\text{Ga}}^- - V_{\text{O}}^{++}$ complexes, as a shallow acceptor centre.

Experimental details

Ga₂O₃ growth

Undoped β -Ga₂O₃ sample was grown in a RF-heated horizontal MOCVD reactor with separate inlets to avoid premature reactions in the manifold between oxygen and organometallics precursors. The reactor can operate at low pressure, between 30 and 760 Torr, and at high growth temperature, up to 1000 °C. Trimethylgallium (TMGa) and 5.5 N pure oxygen were used as gallium and oxygen sources, respectively. Argon was used as carrier gas. The TMGa bubbler temperature was fixed at -15 °C in order to obtain a low vapour pressure, and consequently a moderate growth rate of *ca.* 5 nm min^{−1}. The β -Ga₂O₃ layer was grown on C-oriented sapphire substrate using Ga/O ratio, growth temperature and reactor pressure set at 1.4×10^{-4} , 775 °C, and 30 Torr respectively. The layer’s thickness was measured at 450 nm.

X-Ray diffraction

X-Ray diffraction profiles were recorded in $\theta/2\theta$ configuration, using a Rigaku SmartLab apparatus equipped with a Cu-K α_1 source ($\lambda = 0.1541 \text{ nm}$). Optical transmission spectra were measured in the 200–2000 nm spectral range with a Perkin Elmer 9 spectrophotometer.

Raman spectra

Raman spectra were recorded using a Renishaw Invia Reflex micro-Raman spectrometer at room temperature. The samples were excited using a cw Modu-Laser Stellar-REN laser emitting at 514.5 nm with a power of 2–4 mW. The reflecting microscope objective was 50 \times with a NA 0.75; the excitation spot diameter was 1 μm . The back-scattered light was dispersed by a monochromator with a spectral resolution of 1.4 cm^{−1}. The light was detected by a charge coupled device. The typical accumulation time was 30 s. Raman shifts were calibrated using an optical phonon frequency (520.5 cm^{−1}) of a silicon monocrystal. Several reference Raman spectra for beta-Ga₂O₃ single crystal substrates and sapphire c-cut substrates have been also measured.

Hall effect measurement set-up

Ohmic contacts were prepared by silver paint at the four corners of the sample. Hall effect measurements were performed in a Van der Pauw configuration in the temperature range of 300 to 850 K and for magnetic fields perpendicular to the film plane varying from -1.6 to 1.6 T , using a high impedance measurement set-up which was custom designed for measurement of high resistance.

X-Ray photoemission spectroscopy (XPS)

X-Ray photoemission spectroscopy (XPS) measurements were performed with a Phoibos 150 analyzer (SPECS GmbH, Berlin, Germany) in ultra-high vacuum conditions (base pressure 3×10^{-10} mbar). XPS measurements were performed with a monochromatic Al-K α X-ray source (1486.74 eV).

Conflicts of interest

There are no conflicts to declare.

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