Vertical gallium oxide Schottky barrier diodes with improved performance

Small-angle beveled field plate increases power electronics Baliga figure of merit to $0.6GW/cm^2$, matching gallium nitride and silicon carbide devices.

Researchers based in the USA and Japan claim the highest Baliga figure of merit (FOM) of $0.6GW/cm^2$ so far for β-phase gallium oxide (Ga_2O_3) vertical Schottky barrier diodes (SBDs) [Noah Allen et al, IEEE Electron Device Letters, vol40, issue 9 (September 2019), p1399]. The breakdown voltage was 1100V.

The Baliga FOM measures the trade-off between breakdown voltage (BV) and on-resistance. The reported value is competitive with state-of-the-art gallium nitride (GaN) and silicon carbide (SiC) SBDs. One previous report of a Ga_2O_3 SBD gave a Baliga FOM of $0.39GW/cm^2$ with a 2.44kV breakdown voltage.

The team from Virginia Polytechnic Institute and State University and the University of Southern California in the USA, Novel Crystal Technology Inc in Japan, and the US Naval Research Laboratory used a small-angle beveled field plate (SABFP) and non-punch-through (NPT) design to achieve the high FOM.

Field plates (FPs) are used to massage electric fields, reducing peak values for a given bias. The NPT design consists of a lightly doped drift layer, which contains all of the space-charge region even at breakdown. In punch-through (PT) designs, by contrast, the space-charge region begins to encroach on the more heavily doped lower region of the device. PT designs enable higher breakdown voltages, but at the cost of higher on-resistance.

The researchers comment: "The NPT design is particularly critical for Ga_2O_3 devices as it makes them competitive with vertical GaN and SiC devices despite the higher bulk electron mobility in GaN and SiC."

Ga_2O_3 is being explored for high-power and high-voltage application due to its high expected critical field of order 8MV/cm, resulting from its ultra-wide bandgap of 4.8eV, compared with 3.3–3.4eV for GaN and SiC. The electron mobility of Ga_2O_3 is over $200cm^2/V\text{-}s$. Another attractive feature is the availability of large-diameter Ga_2O_3 substrates. Novel Crystal Technology has spec sheets for 2-inch diameter and 10mmx15mm substrates.

The Ga_2O_3 drift layer was grown by halide vapor phase epitaxy (HVPE) on 2-inch tin-doped n^+-Ga_2O_3 substrates (Figure 1). The doping donor concentration (ND) of the drift layer was in the range $3.0–3.5x10^{16}/cm^3$.

Device fabrication was initiated with thinning the substrate from 652μm to 400μm, using mechanical grinding and polishing/chemical mechanical planarization (CMP). The aim of this step was to reduce series resistance.

Spin-on-glass (SOG) served both as a hard mask for mesa etching and as the field-plate dielectric/support. A 45°-bevel was achieved by hydrofluoric acid wet etching of the SOG hard mask through patterned photoresist (PR), and then inductively coupled plasma etch of the Ga_2O_3 with boron trichloride reactive ions. The bevel/mesa etch depth was ~1μm.

The shallower bevel structure was obtained using a bilayer mask that consisted of 450nm SOG followed by 200nm of plasma-enhanced chemical vapor deposition (PECVD) silicon dioxide (SiO_2). The SiO_2 layer speeded up the lateral wet etch under the photoresist through diffusion along the PR/SiO_2/SOG interfaces. This enabled reduction of the bevel angle from 45° to 1°.

The devices were completed with the deposition of SOG for the field-plate dielectric, backside annealed titanium/gold Ohmic contact formation, and creation of the Schottky contact/FP with wet etch of an opening in the SOG and nickel/gold deposition.

The 45° (BFP) and 1° SABFP devices were compared against Schottky barrier diodes (SBDs) with no FP and with a standard surface FP (Figure 2).

The SABFP SBD demonstrated an on–off current ratio of almost 10^9. The ideality was 1.2 — the excess over unity is attributed to lateral inhomogeneity of the Schottky barrier height. The effective barrier height was ~1.2eV. The differential on-resistance (R_{on}) was $\sim 2m\Omega\text{-}cm^2$ normalized according to the Schottky anode area. The comparison devices delivered similar on-resistance performance. The low value was enabled by the reduced substrate thickness.

Destructive breakdown (BV) under reverse bias occurred at 1100V, which compared with 650V, 400V and 200V for the BFP, SFP and no FP SBDs, respectively. Traces of burning were observed at the Schottky contact edges.

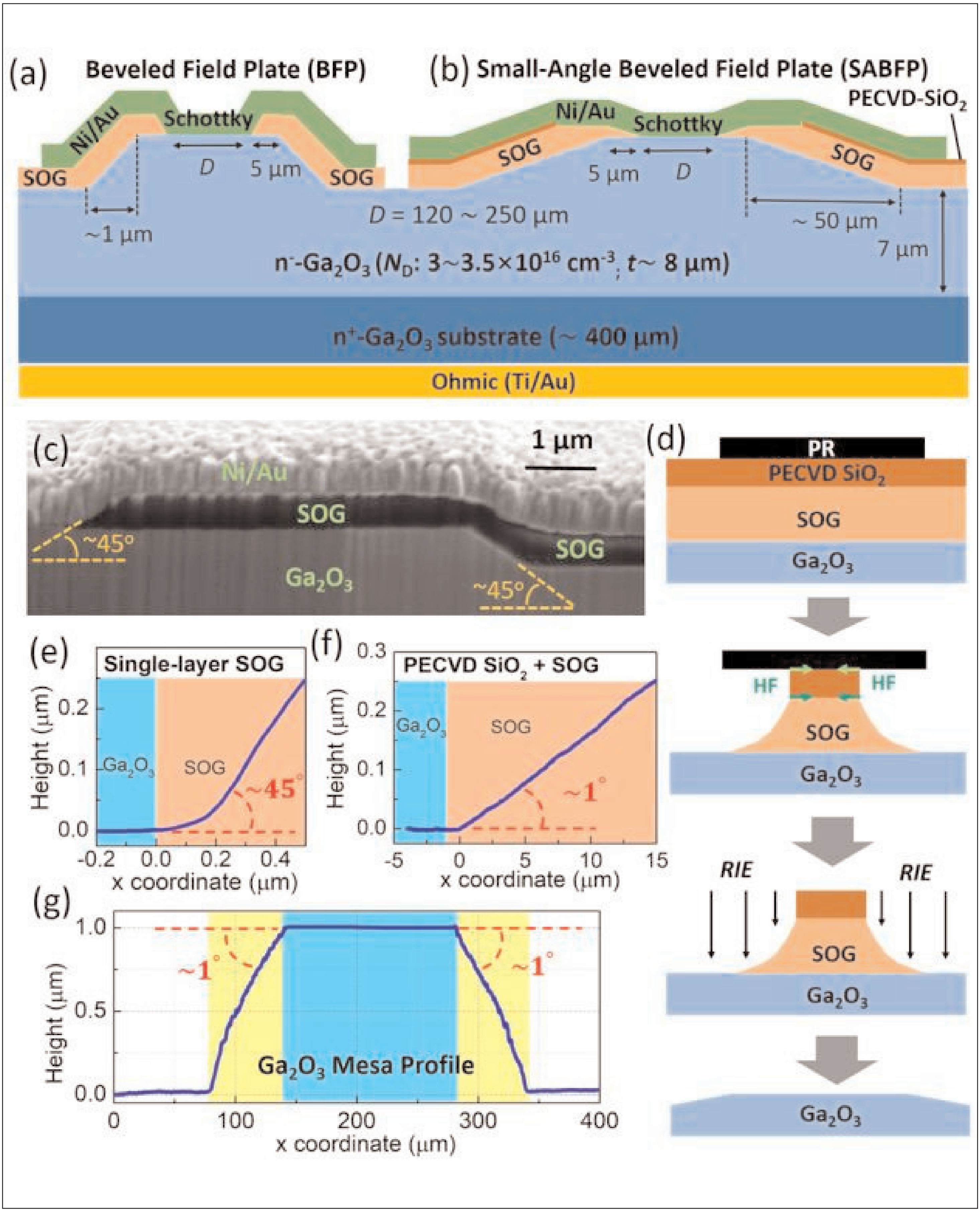

Figure 1. Schematics of vertical Ga_2O_3 SBDs with (a) BFPs and (b) SABFPs. (c) Cross-sectional scanning electron microscope images of BFP structure. (d) Key process steps for fabricating SABFP structure using SiO_2/SOG bilayer mask. SOG surface profiles after wet etch (e) without and (f) with a SiO_2 interlayer. (g) Surface profile of Ga_2O_3 mesa after dry etch using small-angle bilayer mask.

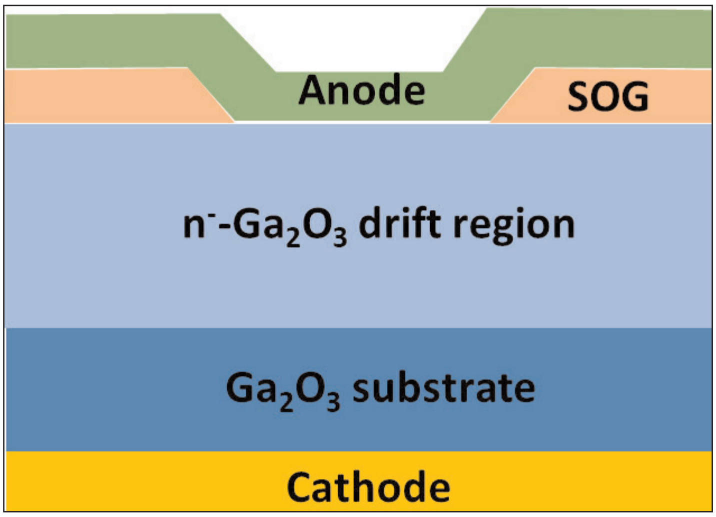

Figure 2. SFP structure.

Simulations of the SABFP device suggested that the peak electric fields at 1100V reverse bias were 3.5MV/cm in the Ga_2O_3 and 9MV/cm in the SOG. Experiments on SOG suggested that 9MV/cm was the field point where exponential leakage begins.

The simulations also suggested that, since the depletion region only reached around 7μm into the structure, some reduction in on-resistance could be achieved by reducing the drift layer from 8μm to around 7μm without compromising the NPT design.

The team reports (Figure 3): "Our SABFP-SBDs shows a FOM [figure of merit (BV^2/R_{on})] of 0.6GW/cm^2, which is the highest in all Ga_2O_3 SBDs reported and is comparable to the state-of-the-art vertical GaN SBDs." The researchers also point out that their simulated peak field of 3.5MV/cm in the Ga_2O_3 exceeds the critical field in GaN or SiC. Indeed, state-of-the-art vertical GaN SBDs have only achieved under 3MV/cm. ■

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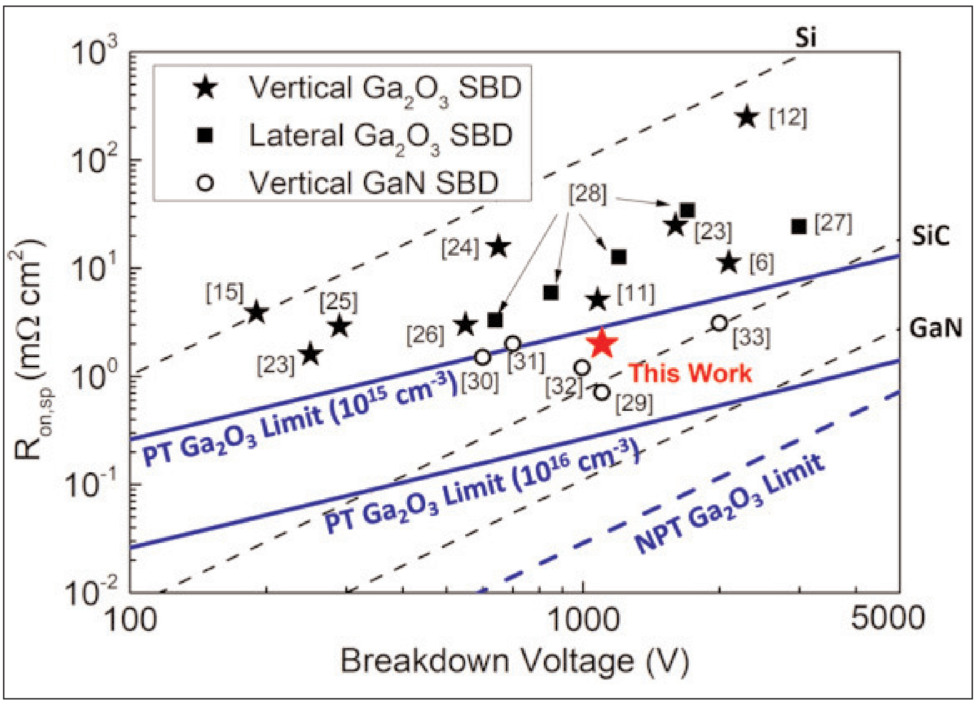

Figure 3. R_{on} against BV for reported vertical and lateral Ga_2O_3 SBDs and vertical GaN SBDs. Theoretical limits of Si, SiC, GaN and Ga_2O_3 NPT, and Ga_2O_3 PT designs with ND values of 10^{15}/cm^3 and 10^{16}/cm^3 are plotted. (Ga_2O_3 limits assume 300cm^2/V-s electron mobility and 8MV/cm critical field.)