Planar Schottky diode with a Γ-shaped anode suspended bridge

A Shurakov[1], D Mikhailov[1,4], I Belikov[1], N Kaurova[1], T Zilberley[2], A Prikhodko[1,4], B Voronov[1], I Vasil'evskii[3] and G Goltsman[1,4]

[1] Moscow Pedagogical State University, Moscow 119435, Russia

[2] Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region 141701, Russia

[3] National Research Nuclear University MEPhI, Moscow 115409, Russia

[4] National Research University Higher School of Economics, Moscow 101000, Russia

Abstract. In this paper we report on the fabrication of a planar Schottky diode utilizing a Γ-shaped anode suspended bridge. The bridge maintains transition between the top and bottom level planes of a 1.4 μm thick GaAs mesa. To implement the profile of a suspended bridge and inward tilt of a mesa wall adjacent to it, we make use of an anisotropic etching of gallium arsenide. The geometry proposed enables the fabrication of a diode with mesa of an arbitrary thickness to mitigate AC losses in the diode layered structure at terahertz frequencies of interest. For frequencies beyond 1 THz, it is also beneficial to use the geometry for the implementation of n-GaAs/n-InGaAs heterojunction Schottky diodes grown on InP substrate.

1. Introduction

Nowadays, GaAs is in vast demand in the monolithic microwave integrated circuit receiver technology including development of power amplifiers, frequency multipliers, coherent and direct detectors for both scientific and civilian purposes [1, 2]. GaAs planar Schottky diodes can successfully act as key elements for the development of sources and detectors of electromagnetic radiation. Shift towards terahertz frequencies of observations inspired by the increase of output power provided by modern solid-state sources leads to the need to create new efficient designs and technologies for implementing Schottky diodes based frequency conversion devices. For these purposes, we develop the geometry and fabrication technology of a GaAs planar Schottky diode utilizing Γ-shaped anode suspended bridge. We also suggest that it is beneficial to use the geometry proposed for the implementation of n-GaAs/n-InGaAs heterojunction Schottky diodes grown on InP substrate.

2. Implementation of diodes under study

The geometry of a planar Schottky diode utilizing a Γ-shaped anode suspended bridge is provided in Figure 1. The geometry is meant to enable the fabrication: a) of a diode with mesa of an arbitrary thickness, b) of a diode's on-chip RF circuitry with nanoscale resolution independent of the thickness of a current-carrying semiconductor layer, c) of "short and wide" diodes with reduced parasitic capacitance. To implement the profile of a suspended bridge and inward tilt of a mesa wall adjacent to it, we make use of an anisotropic etching of GaAs. The fabrication process consists of six essential steps:

I.   formation of a Schottky contact;

II. formation of a dielectric layer;

III. formation of an ohmic contact;
IV. formation of a supporting mesa;
V. formation of a cathode outer contact and Γ-shaped anode suspended bridge;
VI. formation of a final mesa.
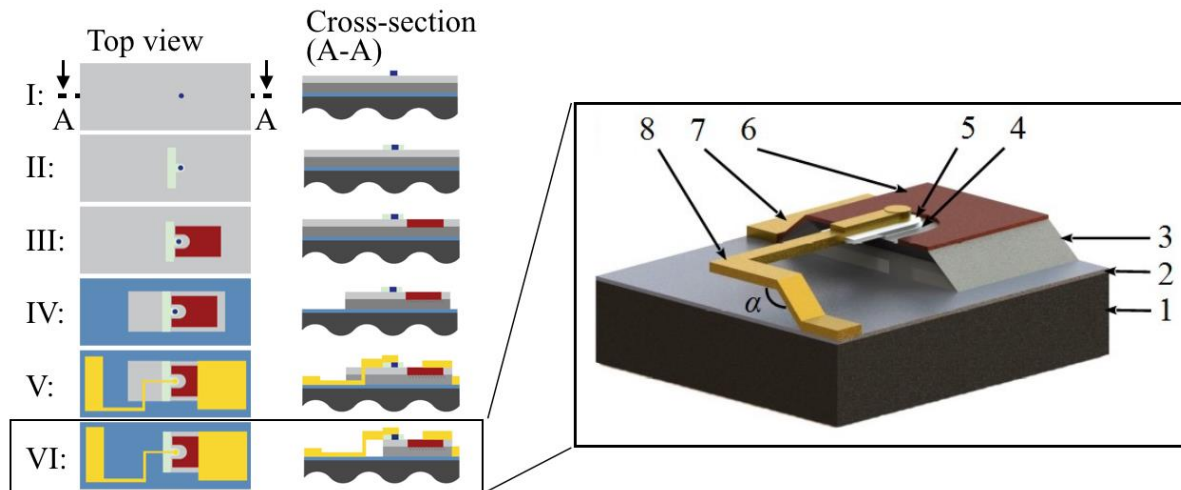
Figure 1. Fabrication steps (I-VI) and resulting geometry of a Schottky diode.

Referring to Figure 1, the handle wafer (1) is presented by a 350 μm thick SI-GaAs layer. The presence of a 50 nm thick $Al_{0.8}Ga_{0.2}As$ etch-stopper (2) enables formation of the n_+/n-GaAs mesa (1200/200 nm with the dopant profile $5\times10^{18}/4\times10^{17}$ cm^{-3}) (3, 4) without lowering of the handle wafer surface plane with respect to the mesa bottom level. The Schottky contact is formed with the aid of Ti/Pt/Au (50/20/20 nm) metallization system deposited on the mesa surface through a 1 μm wide circular opening in 250 nm thick SiO_2 layer (5). However, it is necessary to note that the Schottky contact tip can be fabricated in advance to enhance quality of the metal/semiconductor interface. The ohmic contact to n_+-GaAs (6) is formed on the mesa top surface through an opening in n-GaAs layer and makes use of Ni/Ge/Au/Ni/Au (5/20/35/15/80 nm) metallization system. The cathode outer contact (7) and Γ-shaped anode suspended bridge (8) are presented by Ti/Au (5/450 nm) bilayer whose thickness should exceed total thickness of n-GaAs, SiO_2 layers and can be significantly less than the mesa thickness. Vertical profile of the suspended bridge is determined by the mesa geometry, and the tilt angle (α) equals ~135° if the SiO_2 layer symmetry plane is oriented along the wafer primary flat direction. The bridge width cannot exceed the mesa thickness. The spacing between the Schottky contact and the bridge bend may vary from one thickness of the mesa to several tens of it. In contrast to the air bridge diode technology relying on melting of special photoresist [1], the geometry proposed enables the fabrication of a diode with mesa of an arbitrary thickness. The latter is beneficial for the mitigation of AC losses in the diode layered structure [3] at terahertz frequencies of interest.

3. Results and discussion
The fabrication process described hereinabove was used to produce a set of 22 diodes. We employed a standard IV characteristics analysis [4] to evaluate number of occurrences (N) of the values of series resistance (R_s), ideality factor (η) and barrier height (Φ_{bf}) for the samples produced. All IV characteristics were measured at room temperature. The statistics and SEM images of the diodes are provided in Figure 2(a). As one can clearly see, the Γ-shaped anode suspended bridges are partly shunted by n_+-GaAs layer residuals, which affect DC performance. For a diode with non-shunted bridge, the existence of such a residual electrically connected to mesa results in the appearance of additional bridge-to-mesa capacitance parasitic in terms of AC performance. Both issues can be

resolved via the reiteration of a final mesa etching at the cost of excessive removal of n_+-GaAs under SiO_2 layer. This manipulation enables the fabrication of diodes with ideality factor of 1.2 and series resistance as low as 4 Ω (Figure 2(b)). The spacing between the Schottky contact and the bridge bend is equal to 20 µm for the diodes produced. In case of a feasible 2 µm spacing, EM modelling [4] suggests the diode total parasitic capacitance (C_{tot}) of ~3 fF.
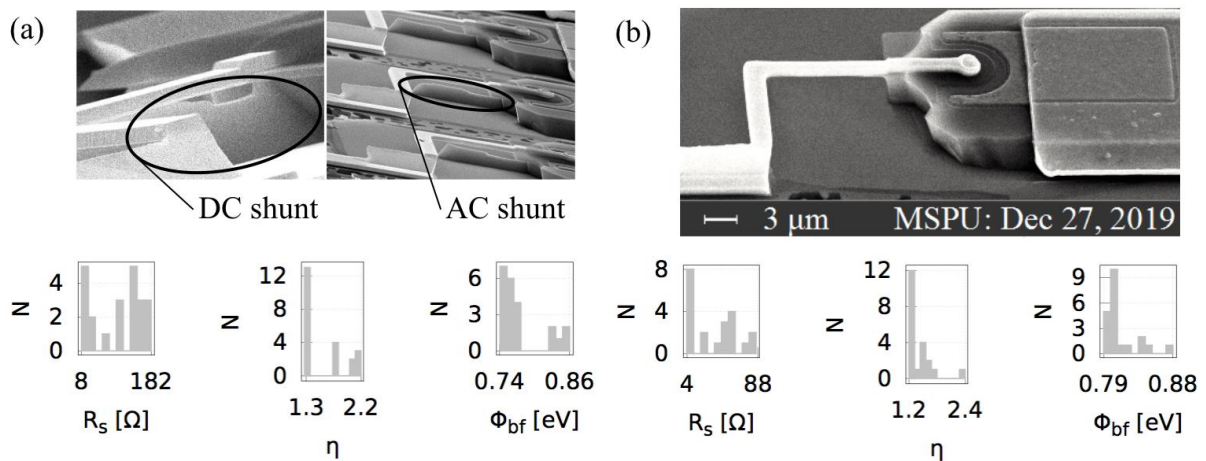
Figure 2(a, b). (a) SEM images (top panel) and statistics on crucial parameters (bottom panel) of diodes after fabrication step VI. **(b)** SEM image (top panel) and statistics on crucial parameters (bottom panel) of diodes after additional iteration of a final mesa etching.

Since planar Schottky diode with a Γ-shaped anode suspended bridge can be simultaneously compact and low-loss, it is considered as a good candidate for pixel of a terahertz camera. In this terms, it seems beneficial to employ the geometry proposed for the implementation of diodes utilizing InP substrate. The use of this substrate enables the epitaxial growth of the n-GaAs/n-In$_{1-x}$Ga$_x$As interfaces characterized by composition-dependent barrier height ($\Phi_b(x)$) [5, 6], which can be set low to enable zero-bias operation of a diode. This is quite attractive in case of a multipixel direct detector. It is also worth mentioning that InGaAs diodes outperform GaAs ones while operated as mixers at frequencies above 1 THz [7]. The possibility to fabricate a Γ-shaped bridge is insured by anisotropic etching of InGaAs [8]. In addition, InP acting as a handle wafer can potentially help to avoid the membrane implementation of a diode-based device. This option is due to the recently discovered strong frequency dependence of a refractive index of indium phosphide at ~1 THz [9]. The structure of n-GaAs/n-InGaAs heterojunction Schottky diode that can be implemented on SI-InP is provided below.
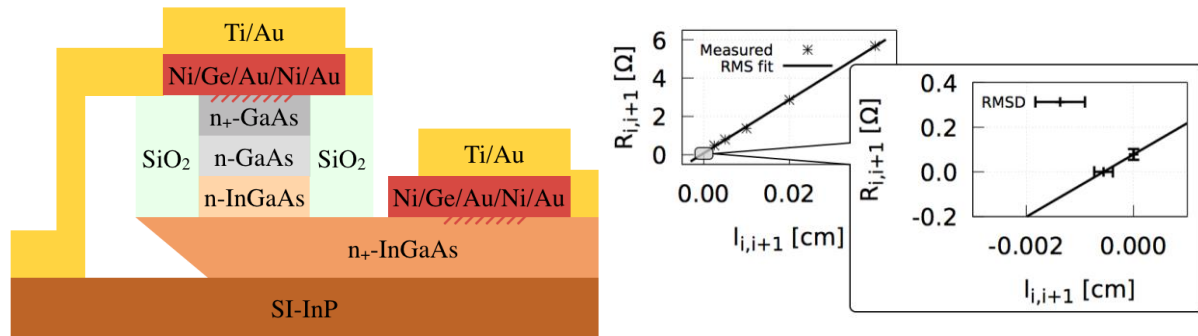
Figure 3(a, b). (a) Structure of a heterojunction diode proposed. **(b)** Results of the transmission line measurements.

Prior to the actual switching to the GaAs/InGaAs/InP platform, we decided to estimate its compatibility with our existing GaAs Schottky diode technology. Referring to Figure 3(a), the cylindrical heterostructure with a radius (r) of ~1 μm and height of a few tenth of a micron is formed to produce a low-capacitive rectifying contact. The top part of the structure contains layers identical to those of the GaAs diodes with Γ-shaped bridges discussed earlier. Thus, the ultimate series resistance value can be predicted, once the contact resistivity of the ohmic contact to n_+-InGaAs is known. To fabricate the contact, we made use of a 1 μm thick n_+-In$_{0.53}$Ga$_{0.47}$As with a doping level of 1.06×10^{19} cm^{-3} grown on SI-InP (Fe-doped, (100) oriented) and the multilayer metallization system identical to that employed in case of the GaAs diodes. Transmission line method was used to evaluate the ohmic contact fabricated. The transmission line samples were annealed at temperature of 360°C in the atmosphere of N$_2$ for 60 s.

We conducted the series of successive measurements of the resistance values ($R_{i,i+1}$) of transmission line sections confined by pairs of neighbouring contact pads. The measurements were carried out with the aid of a source-meter operated in a four-wire mode to eliminate the parasitic impact of probe-to-pad contact resistance. The width of the transmission line under study was equal to 600 μm. The length (l_c) and width (w_c) of each contact pad equaled 250 and 650 μm, respectively.

As shown in Figure 3(b), the resistance values obtained within the experiment obeyed a linear dependence on the distance ($l_{i,i+1}$) spacing neighbouring contact pads, between which they were measured. Assuming the sheet resistance of the semiconductor part of transmission line (R_{sheet}) to be identical to that of the region laying underneath the ohmic contact pad annealed at certain temperature, one can express this dependence as

$$R_{i,i+1} = R_{sheet}\, w_c^{-1} (l_{i,i+1} + 2l_t). \qquad (1)$$

Thus, the slope of the function defined by Eq. 1 provides the value of R_{sheet} if w_c is known. The transfer length (l_t) can be obtained as the intersection point of the extrapolated $R_{i,i+1}(l_{i,i+1})$ curve with the abscissa axis multiplied by a factor of -0.5. The value of contact resistivity ($\rho_{c,TLM}$) is further calculated as

$$\rho_{c,TLM} = R_{sheet}\, l_t^2. \qquad (2)$$

Transmission line method provides no deviation of the l_t value from that intrinsic to the transmission line structure if the value stays within the range from $0.63 t_{SC}$ to $0.63 l_c$ [10]. Here t_{SC} is the semiconductor thickness. Given that we measured $l_t = 2.8$ μm, the corresponding value $\rho_{c,TLM} = 0.7$ μΩ·cm^2 was considered an intrinsic one. In addition, our study of the ohmic contacts to n_+-GaAs revealed that contact resistivity (ρ_c) of ~0.15 μΩ·cm^2 is expected for the diodes possessing series resistance as low as 5 Ω.

$$R_{s,HD} = \rho_c\, (\pi\, r^2)^{-1} + R_{epi} + R_{spread} + \rho_{c,TLM}\, S^{-1} \qquad (3)$$
$$F_c = (2\pi\, R_{s,HD}\, C_{tot})^{-1} \qquad (4)$$

The series resistance of the heterojunction diode ($R_{s,HD}$) is defined by Eq. 3. Here R_{epi} is the excess resistance of n-GaAs in case of its thickness exceeding depletion width, R_{spread} is the spreading

resistance of n$_+$-InGaAs. If the area of the ohmic contact to n$_+$-InGaAs (S) equals 15×15 μm^2 and the linear dimensions of the current-carrying n$_+$-InGaAs section of 2 μm × 15 μm × 1 μm ($L×W×H$) are chosen, one obtains $R_{s,HD} \approx 4.78 + 0 + 0.26 + 0.31 = 5.35$ Ω. The calculation relies on the electron mobility in n$_+$-InGaAs of 3000 cm^2·(V·s)$^{-1}$ measured at room temperature. Given that $C_{tot} = 3$ fF in the case of a 2 μm long straight section of the bridge adjacent to the Schottky contact, the cut-off frequency (F_c) of the diode's input frequency range defined by Eq. 4 equals 9.9 THz. As a rule of thumb, this value has to be decreased by a factor of 10 for a practical diode-based device which suggests its efficient operation up to ~1 THz.

4. Conclusion

We propose the geometry and fabrication route of a planar Schottky diode with a Γ-shaped anode suspended bridge. The geometry enables the fabrication of a diode with mesa of an arbitrary thickness to mitigate AC losses at THz frequencies. Vertical profile of the bridge is determined by the mesa geometry, and the bridge width cannot exceed its thickness. For the diodes fabricated, the bridge maintains transition between the top and bottom level planes of a 1.4 μm thick GaAs mesa with the tilt angle of 135°, ideality factor of 1.2 and series resistance of 4 Ω are achieved. The spacing between the Schottky contact and the bridge bend may vary from one thickness of the mesa to several tens of it. EM modelling suggests total parasitic capacitance of 3 fF for the spacing of 2 μm. For operating frequencies beyond 1 THz, it is beneficial to use the geometry proposed for the implementation of n-GaAs/n-InGaAs heterojunction Schottky diodes grown on InP substrate.

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