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Crystal defects in epitaxial InP layers: electrical and scanning electron microscope study

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Electrical characteristics of *p*-type Au/InP Schottky junctions with Pt nanoparticles sandwiched in epitaxial layer have been studied and compared with reference samples. Various anomalies have been obtained, some of them are similar to the behavior of quantum dot structures. However, it is concluded that the obtained electrical anomalies are connected with pinhole-like defects originated from the break of the epitaxial layer during preparation.

Исследованы электрические характеристики переходов Шоттки в Au/InP *p*-типа с наночастицами Pt, введенными в эпитаксиальный слой; результаты сопоставлены с характеристиками образцов сравнения. Обнаружены различные аномалии, некоторые из них аналогичны поведению структур квантовых точек. Сделан, однако, вывод, что наблюдаемые аномалии связаны с дефектами точечного типа, обусловленными разрывами эпитаксиального слоя в процессе его нанесения.

Although the formation of Schottky junctions to InP is widely studied [1, 2], the question has not been solved until now. It is very difficult to prepare a Schottky junction on InP with appropriate barrier height and ideality factor. The original aim of this work had been to study the effect of Pt nanoparticles sandwiched in the epitaxial layer on the electrical characteristics of *p*-type InP Schottky junctions [3]. However, the electrical behavior of the junctions exhibited various anomalies. For making clear their origin, the wafers were studied by scanning electron microscopy. In this paper, the relation between the defects obtained by this method and the electrical characteristics is discussed.

Three different types of epitaxial InP structures have been studied. One type of the structures contained Pt nanoparticles. About 2 μm thick Zn-doped InP layers were grown on *p*-type Zn-doped <100> oriented InP substrates by liquid phase epitaxy. The growth was interrupted, and Pt nanoparticles of few nm size were deposited by laser ablation. Then the epitaxial growth was continued. The thickness of the upper part of the epitaxial layer and the nominal value of free hole concentration therein were 1 or 0.5 μm, and $3\cdot10^{16}$ or $1\cdot10^{17}$ cm^{-3}, respectively, (samples PtA and PtB), selected so that the Pt nanoparticles would be outside of the depletion layer at zero bias. Two types of reference wafers were also grown. One without breaking the epitaxial growth, with nominal free hole concentration $3\cdot10^{16}$ cm^{-3} (sample Ref1), and two wafers with interruption of the epitaxial growth, but with nominal free hole concentrations of $3\cdot10^{16}$ and $1\cdot10^{17}$ cm^{-3} (samples Ref2A and Ref2B, respectively). The growth conditions are summarized in Table.

Au–Sn/Au ohmic contacts were prepared on the backside of the wafers by thermal evaporation followed by annealing at 350 °C for 10 s. Au Schottky contacts of 0.31 mm diameter were evaporated through a shadow mask on the front side of the wafers. The electrical characteristics were studied by d.c. current-voltage (I-V) and capacitance voltage (C-V) measurements in darkness

Table. The growth conditions, the nominal doping level (N_d), the apparent free hole concentration (n) and the apparent barrier height ($q\varphi_{bX}$) obtained from the capacitance-voltage measurements, the apparent barrier height ($q\varphi_{bI}$), the ideality factor (n) and the rectifying ratio (R_r) obtained from the current-voltage measurements at 300 K, for the studied p-InP wafers

Wafer	Growth conditions	N_d (cm^{-3})	n (cm^{-3})	$q\varphi_{bC}$, (eV)	$q\varphi_{bI}$, (eV)	n	R_r
Ref1	No break, no Pt	$3\cdot10^{16}$	$3.4\cdot10^{16}$	0.70	0.71	1.21	10^6–10^{7*}
Ref2A	Break, no Pt	$3\cdot10^{16}$	$1.4\cdot10^{16}$	0.87	0.70	1.4	10–10^{3*}
PtA	Break + Pt	$3\cdot10^{16}$	$1.2\cdot10^{16}$	0.86	0.68	1.4	50–10^{4*}
Ref2B	Break, no Pt	$1\cdot10^{17}$	–	–	0.74	1.3	10–20*
PtB	Break + Pt	$1\cdot10^{17}$	$6.3\cdot10^{16}$	1.1	0.77	1.15	50–10^{4*}

* For forward and reverse biases of 0.6 V.

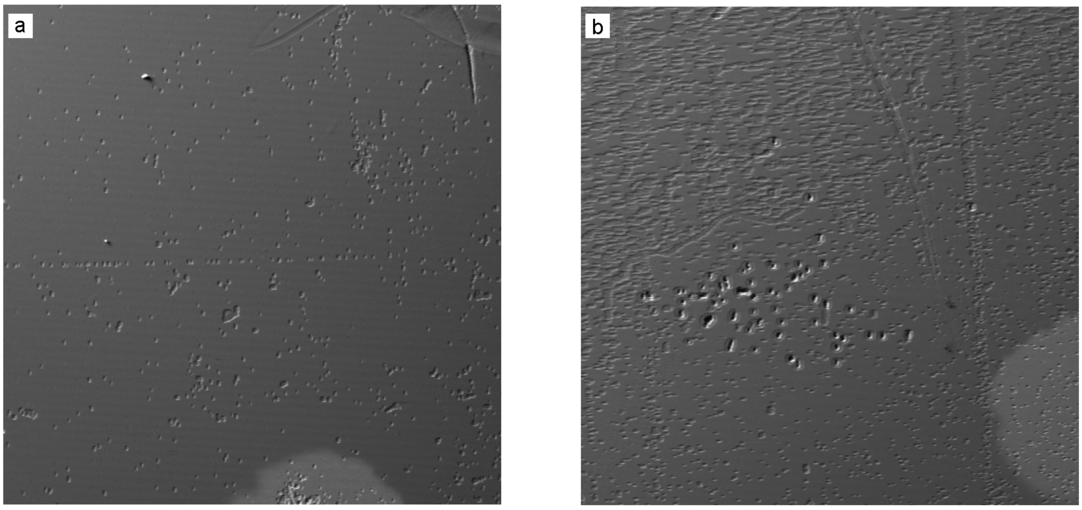

Fig. 1. Typical defect structure of wafers Ref2B (a) and PtB (b). The areas shown are 714×714 μm^2.

within the temperature range of 80 to 320 K. The I-V characteristics were evaluated basing on the thermionic emission theory. The wafers were also studied by scanning electron microscopy.

It was found by the scanning electron microscope study that there were some pinholes in the epitaxial layer on wafer Ref 1, but their estimated density was less than 100 cm^{-2}. In contrast, the wafers prepared with breaking the epitaxial growth exhibited a large density of defects as shown in Fig. 1 for wafers Ref2B and PtB. The estimated defect density is (2 to 8)$\cdot10^7$ cm^{-2} and (3 to 6)$\cdot10^8$ cm^{-2} for wafers Ref2A, Ref2B and PtA, PtB, respectively, depending on the actual wafer area. These defects are also pinholes, but through the upper part of the epitaxial layer grown after the break. They are probably originated from the breaking the epitaxial growth. Wafers with Pt nanoparticles, however, also contained some deep pinholes probably through the whole epitaxial layer, as shown in Fig. 1b.

All the diodes exhibited rectifying behavior at room temperature. The parameters obtained from the room temperature I-V and C-V characteristics, are also presented in Table 1. Junctions prepared with breaking the epitaxial growth exhibited high leakage currents due to defects, as shown in Fig. 2 that presents I-V characteristics of randomly choosen diodes prepared on wafers PtB, Ref1 and Ref2B. The leakage currents had a large scatter for different individual wafers, as indicated by the large scatter of the rectifying ratio presented in Table.

The obtained free hole concentration presented in Table for wafer Ref1 agrees well with the nominal doping level, but it is much lower for other junctions. This phenomenon is also connected with the presence

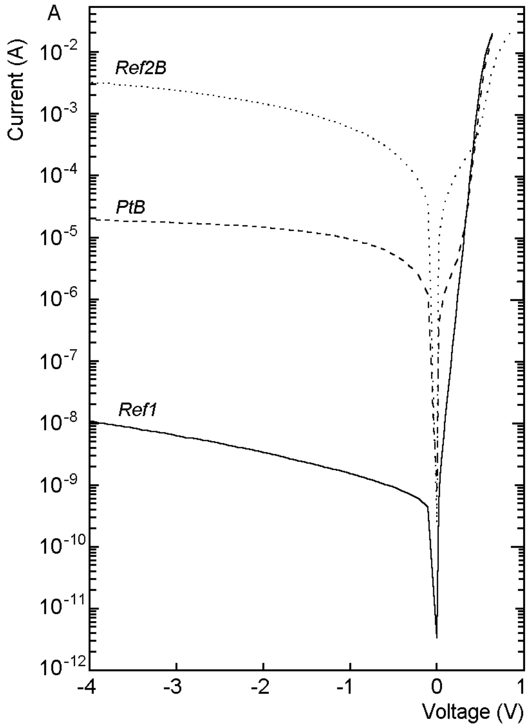

Fig. 2. Room temperature current-voltage characteristics of junctions Ref1, Ref2B and PtB.

of defects acting as compensating deep levels in the upper part of the epitaxial layers.

The apparent I-V and C-V barrier heights are very close for wafer Ref1, while for other wafers, the apparent C-V barrier heights are much higher than the apparent I-V ones. This effect is also connected with the doping level reduction near the InP surface due to compensating deep levels [4]. The apparent barrier heights are higher for wafers with nominal doping level of $1 \cdot 10^{17}$ cm^{-3}. The origin of this phenomenon is not understood yet. The high ideality factors obtained for the junctions PtA, Ref2A, and Ref2B should be connected with the leakage currents [3, 5, 6]. The wafer PtB exhibited much less leakage currents, that is why it has lower ideality factors.

The I-V characteristics for wafers Ref1, Ref2A, and Ref2B are presented in Fig. 3 as a function of the temperature. The leakage currents through junctions Ref2A and Ref2B responsible for the reverse I-V characteristics and for the excess currents in the forward branches at low biases, exhibit very weak temperature dependence. This indicates that the leakage currents are due to the field emission (FE). The higher leakage current level for junctions Ref2B with higher nominal doping level confirms the FE predomination. For junctions Ref1, the current is also dominated by FE in the temperature range of 80 to 120 K, as seen in Fig. 3. A similar phenomenon was recently observed for Schottky junctions on *n*-type InP [3]. It has to be mentioned that leakage currents were not reproducible, different leakage current levels have been obtained for the same diode at repeated measurements. A similar phenomenon was obtained recently by us for InAs/GaAs quantum dot structures and Al/AlAs/GaAs Schottky junctions, where this effect was also interpreted with the presence of defects [7, 8].

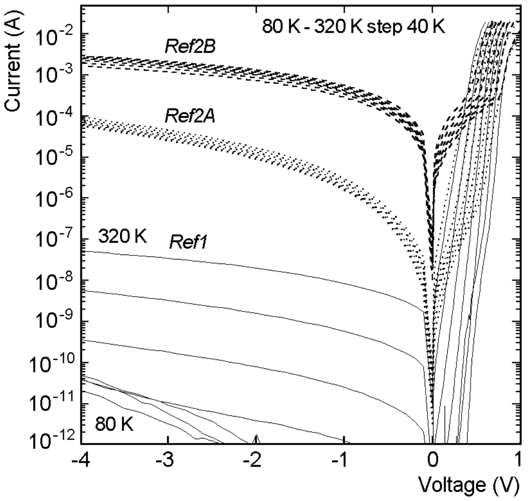

Fig. 3. Current-voltage characteristics of junctions Ref1, Ref2A and Ref2B obtained in the temperature range of 80–320 K at 40 K steps.

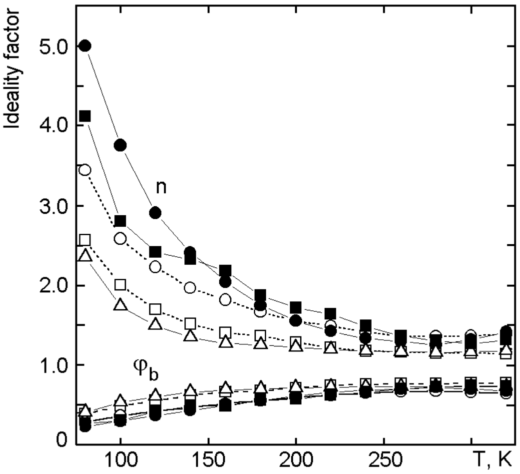

Fig. 4. The apparent I-V barrier heights φ_b and ideality factors n as functions of temperature: Ref1 — open triangles, Ref2A — solid squares, PtA — open squares, Ref2B — solid circles, PtB — open circles.

The apparent I-V barrier heights and ideality factors as functions of temperature are presented in Fig. 4. The temperature dependences of these parameters can be connected either with the lateral inhomogeneity of barrier height [9–11] or with the domination of the current by the thermionic-field emission (TFE) [11–13]. However, the domination of the current by TFE can be connected with the lateral inhomogeneity of the junction, that is, with the local increase of the electric field [12, 13]. The weakest temperature dependence have been obtained for wafer Ref1, the strongest, for wafers Ref2A and Ref2B. The temperature dependence was stronger for structures with higher nominal doping (Ref2B and PtB), than for lower nominal doping level (Ref2A and PtA). This indicates that in the studied structures, the temperature dependence of the apparent barrier height and ideality factor is mainly due to the TFE.

The apparent C-V barrier height slightly decreases with increasing temperature for wafers Ref1, Ref2A and PtA in agreement with the temperature dependence of the band gap. (Wafers Ref2B and PtB have not yield reliable C-V results because of high leakage currents.) This behavior is typical of *n*-type Schottky junctions, but unusual for *p*-type ones. It indicates that interface states are bound to the conductance band edge. (A detailed analysis has been published elsewhere [14]).

Step-like capacitance-voltage characteristics have been obtained for some diodes on wafer PtB as shown in Fig. 5. Such characteristics are typical of quantum structures [15–17] and were also obtained recently by us for InAs/GaAs quantum well and quantum dot structures [18]. However, as this feature is not typical of the whole wafer, it can be concluded that it is connected with the defects detected by scanning electron microscopy.

To conclude, the defect structure and electrical characteristics of *p*-type Au/InP Schottky junctions with Pt nanoparticles sandwiched in the epitaxial layer have been studied and compared with reference samples. It has been found that the break of the epitaxial growth yields pinhole-like defects in the epitaxial layer. Although some electrical features obtained for the structures with Pt nanoparticles are similar to the behavior of quantum dot structures, it has been concluded that the obtained electrical anomalies are connected with defects originated from the interruption in the epitaxial layer preparation.

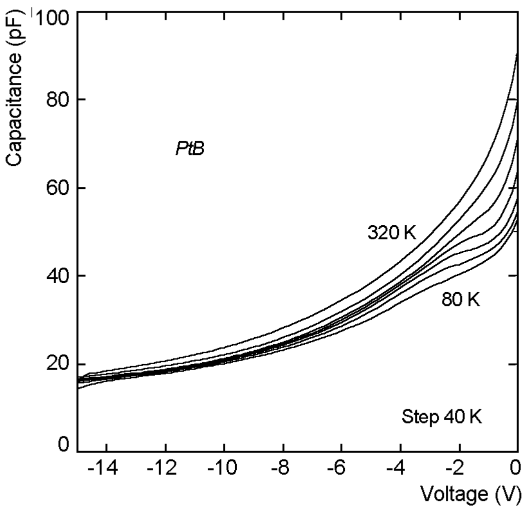

Fig. 5. Step-like capacitance-voltage characteristics of a diode on wafer PtB.

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Дефекти кристалів в епітаксійних шарах InP: дослідження електричними методами та сканувальною електронною мікроскопією

Ж.Й.Хорват, А.Л.Тот, В.Раковіч, З.Пасті, Д.Петьо

Досліджено електричні характеристики переходів Шотткі в Au/InP *p*-типу з наночастинками Pt, введеними в епітаксійний шар; результати зіставлено з характеристиками зразків порівняння. Виявлено різноманітні аномалії, деякі з них аналогічні поведінці структур квантових точок. Зроблено, однак, висновок, що виявлені аномалії пов'язані з дефектами точкового типу, обумовленими розривами епітаксійного шару в процесі його нанесення.