EDGE INSTABILITY ELIMINATION OF GaAs/AlGaAs MQW AVALANCHE TRANSIT TIME OSCILLATORS BY P$^+$ SUBSTRATE

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ABSTRACT: *The p$^+$ substrate plays an important role on the edge stability of p$^+$n multiquantum well avalanche transit time devices. The p$^+$n multiquantum well avalanche transit time devices on n$^+$ substrate easily burn out along the device edge at low breakdown current. The same structure on p$^+$ substrate can have the desired band diagram on device edge to eliminate edge burn-out and CW operation is thus achieved at 100.3 GHz.* Microwave Opt Technol Lett 40: 196–197, 2004; DOI 10.1002/mop.11326

Key words: *multiquantum well; IMPATT; millimeter-wave*

1. INTRODUCTION

GaAs/AlGaAs multiquantum well (MQW) impact ionization avalanche transit time (IMPATT) devices can have better efficiency than GaAs IMPATT devices at millimeter-wave frequencies [1]. Conventional GaAs IMPATT devices show a fall-off in efficiency at the frequencies above 50 GHz because of the saturation of the ionization rates at high electric fields [2]. An IMPATT device is biased at high electric fields for high-frequency operation. The saturation of ionization rates at high electric fields results in a broadened injected current pulse in a less localized avalanche region and degrades the efficiency. GaAs/AlGaAs MQW IMPATT structures have been proposed to alleviate the ionization rate saturation limitations. The incorporation of GaAs/AlGaAs quantum wells in the avalanche region can dramatically increase the nonlinearity of the avalanche process and lead to a narrow injected current pulse [1]. CW and pulse operation of GaAs/AlGaAs MQW IMPATT devices at around 100 GHz was demonstrated on a p$^+$ substrate instead of the popular n$^+$ substrate [3, 4]. The p$^+$ substrate plays an important and interesting role in the edge stability of MQW IMPATT devices. Quantum wells have the potential to trap carriers and the curved edge of a diode mesa results in an energy-band diagram near the edge that keeps one carrier trapped away from edge and push the other trapped carrier toward the edge. The choice of substrate (p$^+$ or n$^+$) can tailor the edge curvature of a p$^+$n junction to be either an acute angle or an obtuse angle. Thus, the breakdown voltage along curved edge can be higher or lower than the bulk breakdown voltage. The burn-out is caused by the undesired band diagram near the device's edge, together with the carrier trapping of quantum wells, and the p$^+$ substrate can alter the band diagram on the device's edge to prevent edge burn-out. The letter will focus on the mechanism of edge instability of MQW IMPATT devices.

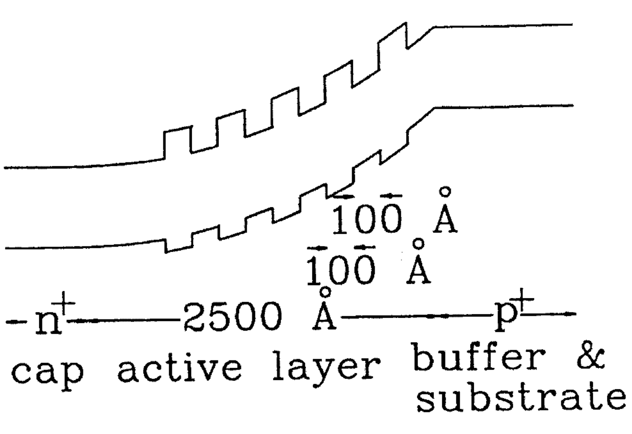


Figure 1 Band diagram of a GaAs/Al$_{0.3}$Ga$_{0.7}$As MQW IMPATT device on a p$^+$ GaAs substrate

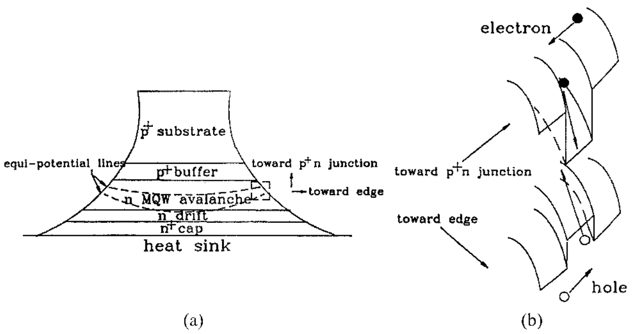


Figure 2 (a) A p$^+$n GaAs/AlGaAs MQW IMPATT diode with p$^+$ GaAs substrate and the epitaxial side is in contact with a heat sink; (b) band diagram near the edge (the area enclosed in the dotted rectangular box) of an MQW IMPATT device

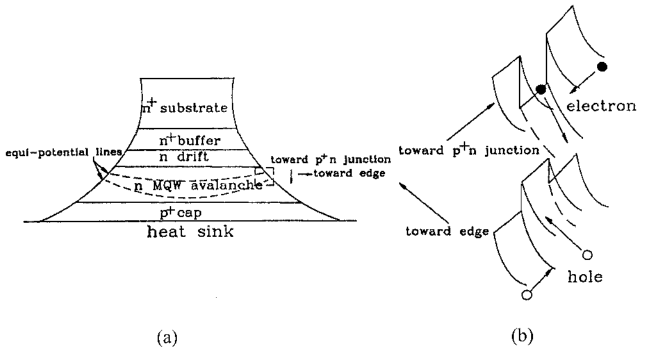
2. DEVICE STRUCTURE AND SUBSTRATE SELECTION ON EDGE INSTABILITY

The band diagram of a single-drift flat profile GaAs/Al$_{0.3}$Ga$_{0.7}$As MQW IMPATT device on a p$^+$ GaAs substrate is illustrated in Figure 1. The p$^+$ substrate eliminates device edge burn-out and will be explained in detail subsequently. The structure is a p$^+$n junction with five periods of MQWs (100-Å barrier length and 100-Å well length) in the avalanche region. The transit time drift region is 1500-Å thick and the corresponding transit time angle is 0.75π at 100 GHz when the electron saturation velocity is 4×10^6 cm/sec. Active layer doping densities of 2×10^{17}/cm^3 for GaAs layers and 1.4×10^{17}/cm^3 for Al$_{0.3}$Ga$_{0.7}$As layers were designed for the simple growth condition of a constant Si flux rate in an MBE system. A novel wafer-thinning integral plated heat-sink technique was developed to fabricate the MQW IMPATT devices [3]. The epitaxial side of the fabricated MQW IMPATT devices is in contact with a plated heat sink in order to dissipate heat efficiently. The fabricated device shows very low leakage current and has the desired hard breakdown voltage at 10 V.

A cross-sectional view of the fabricated diode (p$^+$ substrate) on a heat sink is illustrated in Figure 2. The mesa structure in Figure 2 has a p$^+$ substrate at the apex of the mesa structure and is characterized by a curved edge flaring out from the p$^+$ substrate to a larger base of the n$^+$ cap layer. The curved edge of the diode mesa in Figure 2 results in the equipotential lines bending towards the p$^+$n junction. Thus, the energy-band diagram near the edge—the area enclosed in a dotted square box in Fig 2(a)—can be depicted in Figure 2(b). Because the quantum well has a probability of trapping carriers, the band bending near edge in Figure 2(b) will keep trapped holes away from the edge and push trapped electrons toward the edge. Thus, lower effective doping at the edge causes the breakdown voltage along the diode mesa to be higher and prevents early edge breakdown. If, on the other hand, the MQW IMPATT device was grown on an n$^+$ substrate instead of a p$^+$ substrate, a lower edge-breakdown voltage will occur and cause device failure. The diagram of an MQW IMPATT diode (n^+ substrate) on a heat sink and the corresponding band diagram near the edge are illustrated in Figure 3(a) and (b), respectively. The mesa structure in Figure 3 has n^+ substrate at apex of mesa and a larger base of p^+ cap layer. The curved edge of the diode mesa in Figure 3 results in the equipotential lines bending away from the p^+n junction. Thus, the band bending near mesa edge—the area enclosed in a dotted square box in Figure 3(a)—will keep the trapped electrons away from edge and push the trapped holes toward edge, as illustrated in Figure 3(b). Thus, the higher effective doping along mesa edge causes the edge breakdown voltage to be lower. Edge instability occurs because of the regenerative trapping behavior of multiquantum wells in the case of low edge-breakdown voltage. Instable edge breakdown causes a conduction path to be burned out along diode edge with the result that the current no longer flows through the IMPATT diode, but is shorted around it.

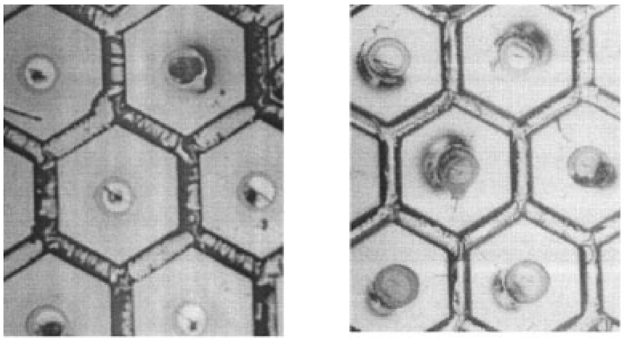
3. EXPERIMENTAL RESULTS

MQW IMPATT devices were fabricated by a novel wafer-thinning integral plated heat-sink technique. A hot (60°C) wet chemical etching solution with H_2SO_4:H_2O_2:H_2O (3:1:1) was used to thin down the device to be less than 10 μm in thickness in order to reduce series resistance. The epitaxial side of the fabricated MQW IMPATT devices is in contact with a plated heat sink to dissipate heat efficiently, as shown in Figures 2(a) and 3(a). Photos of p^+n GaAs/AlGaAs MQW IMPATT diodes with p^+ and n^+ substrates are shown in Figures 4(a) and 4(b), respectively. The diode is 100 μm in diameter with a 75-μm-diameter metal contact on top and an integral plated heat sink at bottom. Both devices have the same layer structures as illustrated in Figure 1, except for different substrates. The devices in Figure 4 were biased at avalanche breakdown and burned out for failure analysis. The strong curvature at the base of the diode mesa caused by the wet chemical etching makes MQW IMPATT devices prone to the edge instability. Experimental results show that very high dc power is needed to burn out devices with p^+ substrate. All of the diodes in Figure 4(a) were burned out at the spot where the diode was probed and at the same dc power level. On the other hand, all of the diodes with n^+ substrate were burned out with extremely low dc breakdown current and the burning started at the edge, as shown in Figure 4(b). Due to the edge-breakdown instability consideration, only p^+n MQW IMPATT structures on p^+ substrate can achieve high-frequency oscillation. The diode was separated and the device area was adjusted by the trim procedure to have approximate 1 pf at zero bias for RF testing. CW oscillation at 100.3 GHz was obtained with 6.4 mW at 364-mA bias current for a diode under test in a W-band reduced-height waveguide Kurokawa-type oscillator circuit. Devices tested in a pulsed mode showed oscillation at 94 GHz with power of 127 mW and 2.2% efficiency [3].



(a) (b)

Figure 3 (a) A p^+n GaAs/AlGaAs MQW IMPATT diode with n^+ GaAs substrate and the epitaxial side is in contact with a heat sink; (b) band diagram near the edge (the area enclosed in the dotted rectangular box) of an MQW IMPATT device



(a) (b)

Figure 4 All diode shown were burned out for failure analysis: (a) photo of p^+n GaAs/AlGaAs MQW diodes (p^+ substrate) on a plated heat sink; (b) photo of p^+n GaAs/AlGaAs MQW diodes (n^+ substrate) on a plated heat sink

4. DISCUSSION AND CONCLUSION

Instability on edge breakdown has been observed for the p^+n GaAs/AlGaAs MQW IMPATT diodes with n^+ substrate. The strong curvature at the base of the diode mesa together with the carrier trapping of quantum wells makes MQW IMPATT devices prone to edge-breakdown instability. The weak edge breakdown of a bulk GaAs IMPATT device can always be compensated by the space charge resistance in the drift region and, thus, a stable edge breakdown occurs [5]. However, the carrier trapping in quantum wells will have a regenerative effect and cause edge-breakdown instability and device failure. Fortunately, it is evident from experiments that p^+n GaAs/AlGaAs MQW IMPATT diodes with p^+ substrate can eliminate edge-breakdown instability because of the proper band bending near the device edge. In summary, the mechanism of edge instability in MQW IMPATT devices has been identified and CW operation of p^+n GaAs/AlGaAs MQW IMPATT devices was realized with the help of p^+ substrate to eliminate edge-breakdown instability.

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