

Effects of Optical Irradiation on III-V Avalanche Photo Diodes

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Abstract: RF properties and avalanche noise generation in opto sensitive GaN/ AlGa_N avalanche photo diodes with and without optical injection have been studied. The optimum frequency and RF characteristics undergo sufficient variation with increase of intensity of optical radiation, which opens the prospects of RF tuning and it's use as a low noise optical detector.

1. Introduction

The research activity in the development of small size mm-wave system is gaining importance in recent years with the emergence of mm-wave APD diodes acting as solid state transmitters. The advent of ion implantation and MBE techniques has made possible the realization of APD oscillator based on GaN, which can provide up to a few mW of RF power (P_{RF}) at mm-wave frequencies. For realizing higher P_{RF} from an APD device, one should choose a semiconductor material that has higher value of critical electric field (E_c), saturated drift velocity (v_s) & thermal conductivity (K), since the P_{RF} of an APD is proportional to $E_c^2 \cdot v_s^2$. The authors have designed APD diodes based on wide band gap semiconductor hetero-structure GaN/AlGa_N, because this material offers at least i) $10 \times E_c$, (ii) $1.5 \times v_s$ and (iii) $3 \times K$, in comparison to those of Si, GaAs and InP. That means GaN/ AlGa_N hetero-structure APD are likely to produce $400 \times P_{RF}$ than its Si / GaAs counterparts. This possibility has been investigated by studying the DC and small signal properties of flat (n++ n- p++) type GaN/AlGa_N SDR (Single Drift Region) APD diodes simulated for operation at Ka-band. In actual experimental fabrication of GaN epiwafers, there occurs a lattice-mismatch strain between n-epilayers and n++ substrates. This strain can be minimized by incorporating a n-type buffer layer in between the epilayer and the substrate [1]. The authors have therefore considered the role of the n-type buffer layer that is introduced in between n - epilayers and n++ substrates. The authors have also simulated flat profile GaN/ AlGa_N APD diodes in order to make a comparative study of the mm-wave properties with those of GaN/ Al Ga_N APD.

Optical control of the dynamic properties of APD devices at mm-wave range can have tremendous application in advanced radars and space-communication systems. Basic process

involved is that, when a photon (due to optical /other radiation) of energy $h\nu$ greater than the band gap of the semiconductor is absorbed at the edges of the reversed biased p-n junction of an APD diode, creation of additional electron-hole pairs takes place within the active region of the diode. These photo-generated carriers give rise to photocurrent and thereby enhance the existing thermal leakage current in the APD diode. The enhanced leakage current alters the avalanche phase delay in the diode, which subsequently modifies the phase and magnitude of terminal current in the device oscillator circuit. The authors have also assessed the performance of the GaN/ AlGaN APD oscillators under optical illumination and the results are reported in the present article.

2. Simulation technique

GaN/ AlGaN APD diodes are first designed and optimized through a generalized double iterative simulation technique used for analysis of p-n junction devices [2]. The method involves iteration over the magnitude of field maximum (E_m) and its location in the depletion layer. The electric field and carrier current profiles are obtained through simultaneous solution of Poisson and current continuity equations. The experimental values of material parameters, viz., realistic field dependence of ionization rates, saturated drift velocities, and mobility of charge carriers in GaN/ AlGaN [3] are incorporated in the present analysis. The junction temperature is assumed to be 300K. The device dimensions, doping and current densities for all types of diodes are optimized for operation at around 35 GHz (Ka-band) after several computer runs.

The maximum RF power output (P_{RF}) from the devices is obtained from the expression:

$$P_{RF} = (V_{RF}^2 G_p \cdot A/2) \quad (1)$$

Where, V_{RF} (amplitude of the RF swing) is taken as $V_B/5$, assuming a 20% modulation of the breakdown voltage V_B and A is cross section of the diode. The diode has been considered to be a circular chip of 50 μm diameter. The diode negative conductance at the optimum frequency ($-G_p$) is normalized to the area of the diode. The space step for the present simulation technique is set as $0.5 \times 10^{-8}\text{m}$. The validity of this simulation method was reported earlier [4].

The leakage current (J_s), entering the depletion region of the reversed biased p-n junction of an IMPATT diode, is normally due to thermally generated electrons and holes [$J_s = J_{ns(th)} + J_{ps(th)}$] and it is so small that electron and hole current multiplication factor,

$$M_{n, p} = J_o / [J_{ns(th)} \text{ or } J_{ps(th)}] \quad (2)$$

Where, [$J_o =$ bias current density] can be considered to be infinitely large. Thus, the enhancement of the leakage current under optical illumination of the devices is manifested as the lowering of $M_{n, p}$. In a GaN/ AlGaN APD structure, the composition of photocurrent may be altered by shining a laser beam selectively on the p^{++} or n^{++} side of the device through fabricated optical windows of appropriate diameter, keeping the diode mounted in a microwave cavity. Thus, the electron saturation current and also the hole saturation current might be enhanced separately, which would produce changes in the small- signal behaviour of GaN based devices. The Top Mounted (TM) and Flip Chip (FC) structures, shown in Figs. 1 and 2, illustrate the optical illumination schemes for generation of electron and hole photocurrents, respectively. In order to assess the role of leakage current in controlling the dynamic properties of GaN/ AlGaN APD oscillators, simulation studies are carried out by the authors on the effect of M_n (keeping M_p very high $\sim 10^6$) and M_p (keeping M_n very high $\sim 10^6$) on (i) the small signal negative conductance, (ii) the RF power and (iii) device negative resistance (Z_{RP}) of flat profile GaN/ AlGaN APD. The details of mathematical calculations based on modified boundary conditions due to enhancement of leakage current are described elsewhere [4].

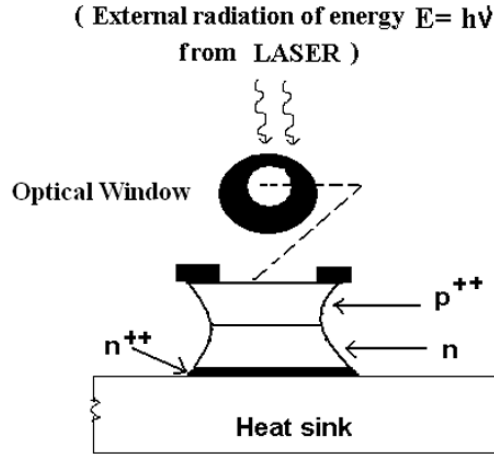


Fig.1. Schematic diagram of a Top Mounted (TM) GaN/AlGaIn APD under optical illumination.

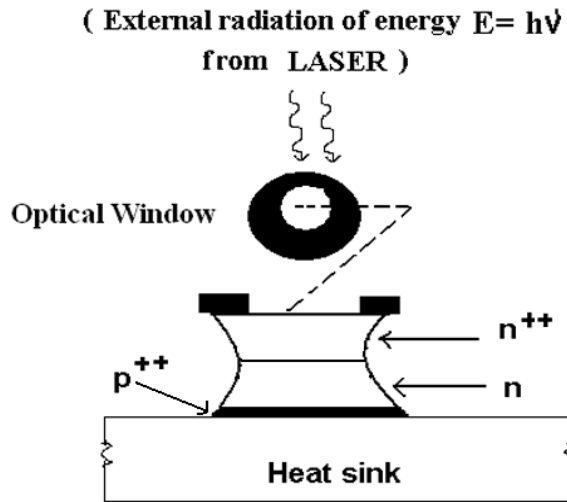


Fig.2. Schematic diagram of a Flip Chip (FC) GaN/AlGaIn APD under optical illumination

3. Results

The dc and small signal properties of various GaN/ AlGaIn APD diode structures are investigated employing the simulation method discussed above. For the sake of brevity, the authors have designated each APD. Abbreviations SD have been used to indicate “Single Drift”. Henceforth, each diode has been referred by respective symbols.

It is seen that the peak electric field (E_m) and the breakdown voltage (V_B) for the GaN/ Al GaIn APD diodes are respectively 5 x and 22-23 x higher than its Si and InP counterparts. Wide band gap (3.3 eV) of GaN/ AlGaIn gives rise to higher electric field. Moreover, the saturated drift velocity of charge carriers in GAN/AlGaIn is almost twice than that in Si and InP. Consequently, the depletion layer width in GaN/ AlGaIn has to be larger. These two factors together give rise to much higher breakdown voltage in GaN/ AlGaIn APD s compared to Si and InP based diodes. The observation also supports the experimental reports [5]. Again, the efficiency (η) of GaN/ AlGaIn APD diodes is found to be higher than that of Si and InP SDR diodes. The ratio of drift region voltage (V_D) to the diode breakdown voltage (V_B) is the highest in the GaN/AlGaIn based APD diodes .The increased value of V_D/V_B ratio in GaN/AlGaIn provides higher efficiency in GaN/ AlGaIn based APD. The device efficiency of 20% for GaN/ AlGaIn APD diodes is much higher as compared to the efficiency of only 9% and 13.6% respectively for Si and InP based diodes. High efficiency and a

high value of V_B are the key factors for higher power output in GaN/ AlGa_N APD devices. It is interesting to note that P_{RF} for GaN/ AlGa_N APD diodes is at least 400 times higher than its Si and InP. These results are highly encouraging for employing GaN/ AlGa_N as a base material in APD fabrication. This relative predominance of hole leakage current in optical control of GaN/ AlGa_N APD s can be attributed to the inequality of the ionization coefficient values in GaN/ AlGa_N APD [3].

4. Conclusions

The dynamic characteristics of GaN/ AlGa_N APD diodes at Ka-band are compared through a simulation technique. The simulation results establish the potential of wide band gap GaN/ AlGa_N as a base material for APD fabrication. A detailed simulation study on the photo sensitivity of GaN/ AlGa_N based APD diodes operating at Ka-band are reported for the first time. The effect of M_p in modulating the mm-wave performance of GaN/ AlGa_N is found to be more prominent than that of M_n . Moreover, the property of change of optimum frequency and of the value of diode negative resistance with optical irradiation can be used for mm-wave tuning and optical detection.

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