A Resonant-Cavity, Separate-Absorption-and-Multiplication, Avalanche Photodiode with Low Excess Noise Factor

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Abstract—We report on the design, fabrication, and performance of a photodiode that combines the advantages of a resonant cavity with a separate-absorption-and-multiplication avalanche photodiode. The device is grown on GaAs using molecular beam epitaxy and is designed to detect light near 900 nm. This photodetector has exhibited the following characteristics: an external quantum efficiency of 70%, a spectral linewidth of less than 7 nm, an avalanche gain in excess of 30, and low dark current. In addition, a low excess noise factor corresponding to 0.2 ≤ k ≤ 0.3 has been achieved.

I. INTRODUCTION

HIGH-SPEED photodetectors are essential components as the transmission rates of optical systems steadily increase. As photodetectors evolve toward higher speeds, it is, of course, important to maintain high quantum efficiency and, for some of the applications that employ wavelength division multiplexing, it would be advantageous to combine wavelength selectivity with detection. The resonant-cavity structure has been shown to alleviate the well-known bandwidth/quantum efficiency tradeoff as well as to provide a narrow spectral response [1]–[4].

For high-bit-rate transmission systems, avalanche photodiodes (APD's) are frequently utilized because they provide a sensitivity margin, compared to p-i-n photodiodes [5]. The APD structure that has been widely deployed for long-wavelength optical communications is the SAM (separate absorption and multiplication) APD [5]–[7]. This type of APD has the advantage of minimizing the tunneling component of the dark current in the absorption region and of providing single carrier injection into the multiplication region. It is well known that a single carrier injection is required in order to reduce the multiplication noise that arises from the stochastic nature of the multiplication process [8].

Previously, we have incorporated a SAM APD into a resonant-cavity structure [9]. In that work, the structure was designed for hole injection based on reports that the hole ionization rate for Al_{0.4}Ga_{0.6}As, which was used for the multiplication region, is higher than that of the electron. Noise measurements subsequently showed, however, that electron injection yields the lowest multiplication noise. In this paper, we describe the design, fabrication, and performance of a resonant-cavity SAM APD that utilizes electron injection from the absorbing region. These APD's have exhibited high external quantum efficiency, low dark current, and low noise.

II. EXPERIMENTAL

The resonant-cavity SAM APD is grown by molecular beam epitaxy (MBE) using Al_{x}Ga_{1-x}As with a strained In_{0.1}Ga_{0.9}As absorption region. The crystal growth is done under an As$_2$ overpressure at 600°C except for the In$_{0.1}$Ga$_{0.9}$As region, which is grown at 540°C. Fig. 1 details the structure of the device. First, the bottom mirror, which consists of 20 pairs of p-type AlAs/GaAs layers, is grown. After the mirror is finished, the growth is interrupted for up to several hours to allow recalibration of the growth rates. Then a p-type Al$_{0.1}$Ga$_{0.9}$As spacer layer and a 500 Å, p-type (1×10$^{16}$/cm$^3$), strained In$_{0.1}$Ga$_{0.9}$As absorption region are grown. The spacer layer thickness is chosen to place the absorption region at an antinode of the optical standing wave, where the absorption is maximized. Growth is interrupted for about 5 min before and after the growth of the absorption region to allow the substrate temperature, doping levels, and growth rates to be changed. A thin 2000-Å p-type (1×10$^{17}$/cm$^3$) Al$_{0.4}$Ga$_{0.6}$As multiplication region is then grown. This is followed by an n$^+$ Al$_{0.4}$Ga$_{0.6}$As spacer layer to form the p-n junction. The total cavity length is designed to be resonant at the desired detection wavelength, in this case 900 nm. Finally, a 50-Å n$^+$ GaAs cap layer is grown to serve as an electrical contact layer and to protect the underlying AlGaAs from oxidation.

Indium is used for the back-side electrical contact and Ni/AuGe is thermally evaporated and photolithographically patterned on the front side to serve as the contact to the n-type top layer. Devices are isolated by etching ~100-μm diameter mesas with a bromine-methanol solution. A top mirror is formed by e-beam evaporation of λ/4 pairs of ZnSe/CdF$_2$. After each pair is deposited, the spectral response of the device is checked. For this device, two ZnSe/CdF$_2$ pairs give the optimum quantum efficiency.

III. RESULTS AND DISCUSSION

After device fabrication, the current–voltage characteristics are measured. Fig. 2 shows the photocurrent, dark current, and avalanche gain as a function of the applied bias. From the
photocurrent measurement, the photodiode is seen to reach punchthrough at about 4 V. At punchthrough, the edge of the depletion region reaches the absorption layer, allowing electrons generated in the absorption layer to be swept into the multiplication layer. In the range of 4–11 V, the photocurrent remains relatively constant, indicating unity-gain operation. The unity-gain photocurrent is used as a reference to determine the multiplication at higher biases. Just below breakdown, near 14 V, the multiplication exceeds 30. At 90% of the breakdown voltage, the dark current is under 10 nA and even at a gain of 30, the dark current is less than 100 nA. As an additional note, the In_{0.1}Ga_{0.9}As region is grown near the critical thickness at which dislocation formation becomes energetically favorable; therefore, some misfit dislocations form and cross-hatching is observed on the surface when viewed by Nomarski phase-contrast microscopy. However, the low dark current is an indication that the number of misfit dislocations is not sufficient to significantly affect the device characteristics.

The spectral response is measured with the device biased at unity gain. The response of the device with two pairs of dielectric mirrors (corresponding to a top mirror reflectivity of 94%) is shown in Fig. 3. The peak external quantum efficiency is 70% at 870 nm, with a full width at half maximum (FWHM) of 7 nm. A 5% decrease in the optical thickness of the cavity can account for the deviation from the designed detection wavelength of 900 nm. That would include uncertainties in the physical thickness and the refractive index. Owing to the narrow spectral response, the layer thicknesses in the cavity are critical. To place the peak responsivity at a desired wavelength, growth rates must be controlled to 1% accuracy. In an MBE environment, in situ monitoring techniques have been shown...
to enable repeatable growth rates to better than 1% accuracy [10].

Multiplication noise is measured with a calibrated noise power meter at 50 MHz and a bandwidth of 4 MHz. The noise is first measured with the device biased for unity gain and then the noise power is measured as a function of gain. The primary photocurrent for these measurements is approximately 100 nA and the incident wavelength is 930 nm. Fig. 4 shows the excess noise factor versus gain. The dashed lines indicate theoretical excess noise factors for several values of $k$, the ratio of the ionization coefficients [8]. The measured excess noise factors (crosses) lie below the line corresponding to $k = 0.3$. These results are comparable to results from multiple-quantum-well APD’s [11]. Other studies [12], [13] have found that for very thin multiplication regions, such as the one studied here, the dead space effect acts to reduce the excess noise factor. We believe that this effect may be playing a role in reducing the excess noise in the resonant cavity SAM APD.

IV. SUMMARY

We have discussed the design and characteristics of an electron-injection resonant-cavity SAM APD. This device demonstrates low dark current, a maximum gain greater than 30, a spectral response with a FWHM of 7 nm, a peak quantum efficiency of 70% at 840 nm, and an excess noise factor corresponding to $0.2 \leq k \leq 0.3$.

REFERENCES


