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Improvement of current leakage in the InAs photodetector by molecular beam epitaxy

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Abstract

I–V characteristics of the unpassivated InAs p–i–n diodes with various i-layer thickness have been systematically studied. At the same reverse bias of -0.5 V, the reverse current density is -0.83 and -0.18 A/cm² for the p–n diodes and p–i–n diodes with a 0.72 - μ m-thick i-layer, respectively. It is obvious that the surface shunt and bulk leakage current are dramatically decreased owing to increasing of the i-layer thickness between p and n layers of InAs p–n junction. Meanwhile, an odd current–temperature behavior; the reverse-bias current decreases with increasing temperature, has been observed in the InAs p–i–n photodetector with a 0.72 - μ m-thick i-layer. Below 90 K, the photocurrent generated by the background thermal radiation should dominate the *I–V* characteristics of the p–i–n diode and the photocurrent increases a little as temperature drops due to the improvement of minority carrier diffusion length. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

InAs infrared photodetectors and infrared light emitting diodes (LEDs) are useful for applications which use 3 – 5 μ m atmospheric window [1–4]. Comparing to the other narrow bandgap III–V semiconductors materials such as antimonide compounds, the prime advantage of InAs is that it can be operated at room temperature [5,6]. Infrared photodiodes are selected according to the following requirement: The product R_0A should

be as high as possible, where $R_0 = (dI/dV)^{-1}|_{V=0}$, A , I , and V are the zero bias differential resistance, diode area, diode current and applied voltage, respectively [5]. The R_0A is degraded by the increase in leakage current. Thus, there is a strong incentive in understanding the leakage current mechanisms in order to minimize the reverse leakage current.

All the bulk properties of a narrow bandgap semiconductors come to an abrupt halt at a surface. The surface usually consists of dangling bonds or bonds that are satisfied by atoms other than the host atoms in the bulk. The dangling bonds and bonding with foreign atoms give rise to a high density of defects at the surface of a

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semiconductor. The Fermi level is pinned by the overall charge state at the surface rather than by charge neutrality in the bulk. Due to the large density of such surface states, there is an enhanced recombination at the surface. A surface pinning effect on the characteristics of p–n junctions has already been reported for the narrow bandgap material [5]. In particular, large current due to tunneling at the surface has been observed. Thus the diode leakage current in narrow bandgap semiconductors are often dominated by carrier transport through the surface where the p–n junction interface meets the free space or a passivation layer. This leakage current depends on the surface potential and can be controlled by varying the passivation techniques or by applying an external voltage to the gate electrode deposited on the passivation layer along the junction perimeter. Adding a third gate electrode is a useful way to study the surface effect on the current–voltage (I – V) characteristics of a p–n junction.

The dark currents of a photodiode determine the device performance, which add excess noise and thus degrade the detector sensitivity. So, there is interest in understanding the dark currents in order to minimize them [4]. In general, the diode dark current at a higher temperature is due to the diffusion mechanism. While at lower temperature, the dark currents show a weakly temperature dependence which are due to the onset of tunneling or a certain shunt current leakage mechanism [5,7–9].

In this paper, temperature-dependent I – V characteristics of the unpassivated InAs p–i–n photodiodes with various i-layer thickness are studied in detail. In addition, we have observed an odd current–temperature behavior in the unpassivated InAs p–i–n diode with 0.72- μm -thick i-layer thickness.

2. Design of the InAs infrared photodiode

In an ideal p–n junction diode, there are two dominant current sources, i.e., injection–diffusion and generation–recombination current. The injection–diffusion current is due to the injection of thermal electrons and holes whose energies are

higher than the built-in potential energy to the other side of the junction and becomes the minority carrier diffusion current. Some of them are reflected back by the junction interface owing to the quantum mechanical reflection. After derivation, the important characteristics of the diffusion current is its exponential dependence, $\exp(eV/kT)$, and e , V , k , and T are electronic charge, applied voltage, Boltzmann's constant and temperature. On the other hand, the generation–recombination current is due to electron–hole pair generation or recombination within the p–n junction depletion region in the bulk or at surface. It also exhibits an exponential dependence, $\exp(qV/2kT)$, while qV is much larger than kT . With the proper choice of E_{F_n} and E_{F_p} , where E_{F_n} and E_{F_p} are quasi-Fermi levels for electrons and holes, the diffusion current can be adjusted to become much smaller than the recombination current at small bias. For a small bandgap material, in order to increase the differential resistance R_0 at zero bias, we have to use high doping p^+-n^+ diodes to increase the built-in potential and reduce the diffusion current. In addition, the defect density in the depletion region and the surface state density near p–n junction perimeter must be also decreased to make less generation–recombination current. However, p^+-n^+ design leads to high tunneling current in low bandgap semiconductor. Therefore, to reduce the diffusion current, we have to use p–i–n structure instead of p–n diode. Besides, the advantage of p–i–n structure relies on its inherent high speed of response, because of its low junction capacitance. Furthermore, it can also improve the quantum efficiency of the detector and decrease the probability of bulk tunneling current. However, it is unclear that whether the insertion of i-layer in between the p–n junction will improve the surface leakage current.

Based on the above consideration, the p- and n-type of InAs p–n layers must be doped in nondegenerate state at 77 K to decrease the tunneling current, i.e., the carrier concentration of 1×10^{18} and $5 \times 10^{16} \text{ cm}^{-3}$ in p- and n-type, respectively. And the i-layers with various thickness are inserted between the p–n junction. To further increase the barrier height for electrons and holes, the high–low junction design (p^+-p ,

n^+-n) is adopted, thus the p^+ cap layer concentration is $1 \times 10^{19} \text{ cm}^{-3}$ and the n^+ buffer layer concentration is $1 \times 10^{18} \text{ cm}^{-3}$. As calculated, the barrier height is enlarged more than 3 kT. Noting that the p-type region thickness must be kept as thin as possible to avoid photogenerated carriers being consumed by the surface.

3. Experiments

The InAs diode was grown on the (100) n-type InAs substrates using VG V80H MK II solid sources molecular beam epitaxy (MBE) equipped with a 15 KV reflection high-energy electron diffraction (RHEED) system. After loading into the growth chamber they were slowly heated to 500°C to remove surface oxide, then a 0.2- μm -thick n-type InAs buffer layer (Si-doped to $1 \times 10^{18} \text{ cm}^{-3}$) was grown to smooth out the surface, followed by a 1- μm -thick n-type InAs active layer (Si-doped to $5 \times 10^{16} \text{ cm}^{-3}$), then an undoped InAs layers (i-layer) with various thicknesses, i.e., 0, 0.10, 0.30, 0.50 and 0.72- μm , were grown. The doping level in the i-layer represents the background doping level in the MBE system. Subsequently a 0.1- μm -thick p-type InAs layer (Be-doped to $1 \times 10^{18} \text{ cm}^{-3}$) was grown, finally a 0.1- μm -thick p-type InAs contact layer (exponentially graded doped from 1×10^{18} to $1 \times 10^{19} \text{ cm}^{-3}$) was deposited. The growth rate was kept at 1- $\mu\text{m}/\text{h}$. The As_4/III beam equivalent pressure (BEP) ratio was maintained about 25 throughout the growth. To fabricate the InAs p-i-n diode, the epilayers are first mesa etched into circular dots having 200 μm diameter. A double layer of 100 nm thick Au-Be and 300 nm thick Au were evaporated and lift-off sequentially to form a p-type ohmic contact. While the n-type ohmic contact was formed by In mounted during MBE.

4. Results and discussion

At room temperature, the I - V characteristics of the unpassivated InAs p-i-n diodes with various i-layer thicknesses, i.e., 0, 0.1, 0.3, 0.5, 0.72 μm , are shown in Fig. 1. At the same reverse bias of

Fig. 1. The room temperature I - V characteristics of the InAs p-i-n diodes with different i-layer thicknesses.

−0.5 V, the reverse current density changes from −0.83 to −0.18 A/cm^2 when the i-layer thickness is increased from 0 to 0.72 μm . It is obvious that the surface shunt and bulk leakage current are dramatically decreased owing to increasing of the i-layer thickness.

In general, the current-voltage relation of a diode can be expressed as $J = J_s[\exp(qV_a/nkT)]$, where J_s , V_a and n are the reverse saturation current density, applied voltage and ideality factor of a diode [10]. For an ideal diode n should be unity. Due to recombination and generation processes in a depletion region of real diodes and the voltage sharing among various parts of the diode, n is larger than unity. In fact, at low applied biases, n is usually larger than unity. Also, for large forward biases, there is a saturation effect due to ohmic losses of the finite resistance of the neutral n- and p-regions. After calculation, n turns out to be 1.19, 1.21, 1.10, 1.11, 1.22 for InAs p-i-n diodes with different thickness i-layers, i.e., 0, 0.1, 0.3, 0.5, 0.72 μm , at forward bias of 0.1 V, respectively. It shows that these ideality factors all approach to unity, suggesting that the p-i-n junction are relatively good.

For the purpose of leakage current analysis on the unpassivated InAs p-i-n photodetectors, their temperature-dependent I - V characteristics were studied in detail [4,6]. At reverse bias $V = -0.5$ V, the reverse current as the functions of reciprocal temperature of InAs p-n diodes and p-i-n diodes with a 0.72- μm -thick i-layer thickness is shown in Fig. 2. Below 80 K, the dark currents of the unpassivated p-i-n and p-n diodes are 1.0×10^{-10} and 8×10^{-6} A, respectively. It is evident that the tunneling current could be successfully suppressed by adding an i-layer between p and n layers of the InAs p-n junction. By the theoretical calculation, it is found that the current level is about 10^{-12} A of an ideal InAs p-i-n diode and found that at least two order of magnitude lower than the experimental value of the InAs p-i-n diodes. It can be explained that the little surface leakage current and background photocurrent dominate in practical InAs p-i-n diodes [6].

Fig. 3 shows a sequence of I - V characteristics of a typical p-i-n diode taken at several temperatures from 40 to 300 K. At 77 K, the breakdown voltage of the unpassivated p-i-n diode exceeds

Fig. 2. The theoretical and experimental reverse current as the functions of reciprocal temperature at reverse bias $V = -0.5$ V of the unpassivated InAs p-n diodes and p-i-n diodes with 0.72- μm -thick i-layer thickness.

13 V. It implies that interband tunneling effect is no longer the dominant breakdown mechanism. For the I - V characteristics of the p-i-n diode measured at lower temperatures ($T < 80$ K), the reverse bias current decreases with increasing temperature which is against the conventional wisdom. If the current transport mechanisms are still ascribed to the diffusion and generation current at this low temperature range, the current level should be higher with increasing temperature due to a higher carrier concentration.

The magnitude of dark current at different temperature are plotted as shown in Fig. 4. Each current temperature curve is extracted under a fixed reverse bias of $V = -0.5$ V. It is clear that the dark currents in Fig. 4 possess an odd current temperature behavior, i.e., the dark current gradually decreases to a minimum value as the temperature changed from 40 to ~ 90 K, and then, it increases with temperature. Above 90 K, I - V characteristics of the p-i-n diode can be well fitted by the diffusion and generation current. Nevertheless, when the temperature is lower than 90 K, the

Fig. 3. The I - V characteristics of a typical p-i-n diode with 0.72- μm -thick i-layer thickness in the temperature range from 40 to 300 K.

Fig. 4. The dark current of the p-i-n diode with 0.72- μm -thick i-layer thickness as the function of temperature at reverse bias $V = -0.5\text{ V}$.

photocurrent generated by the background thermal radiation dominates the I - V characteristics of the InAs p-i-n diode and the photocurrent increases a little as temperature drops due to the improvement of minority carrier diffusion length. Hence, the photocurrent always exists in the high-performance narrow bandgap material unless there is no temperature gradient between the cryostat shielding and the diode. So there exists two current components, i.e., photocurrent and diode dark current, to compete. At the temperature range around 90 K, both currents are comparable.

5. Conclusion

I - V characteristics of the unpassivated InAs p-i-n diodes with various i-layer thicknesses, i.e., 0, 0.1, 0.3, 0.5, 0.72- μm , have been studied in detail. At the same reverse bias of -0.5 V , the

reverse current density changes from -0.83 to -0.18 A/cm^2 of the p-n diodes and p-i-n diodes with 0.72- μm -thick i-layer thickness, respectively. It is obvious that the surface shunt and bulk leakage current are dramatically decreased owing to increasing of the i-layer thickness. In addition, an odd current-temperature behavior, the reverse-bias current decreases with increasing temperature has been observed in the InAs p-i-n diodes with 0.72- μm -thick i-layer thickness. When temperature is lower than 90 K, an additional photocurrent generated by the background thermal radiation should dominate the I - V characteristic of the InAs p-i-n diode and which increases a little as temperature drops due to the improvement of minority carrier diffusion length.

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