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Dark current behaviour analysis for avalanche photodiodes

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Abstract. This paper deals with the results of serial of analytical calculations which have been done on an avalanche photodiode made of germanium with silicon quantum dots (QD) which has multilayers of QDs to determine its characteristics. In these calculations we focus on the main parameters that determine the performance of avalanche photodiode such as tunneling current, photosensitivity, multiplication factor, noise spectral density and avalanche noise factor. The study also compares the results of germanium silicon avalanche photodiode with other avalanche photodiodes made with different materials. The model which has been used for calculation is considered with a separated absorption and multiplication regions operation under several conditions varied between classical and Geiger mode.
Keywords: avalanche photodiode, quantum dot, tunneling current, silicon, germanium, multiplication factor, noise density, photosensitivity.

1. Theory and results

A tunneling current occurs when charge carrier moves through a barrier that they classically shouldn't be able to move through. In other words, charge carriers don't have enough energy to flow over the barrier.

In an avalanche heterophotodiode (AHPD) with separate absorption and multiplication regions (SAMRs) under classical conditions it's possible to find the tunneling current [1] by using the following equation [2]

$$J_T = \sum_{i=1}^{2} J_{Ti} = \frac{\sqrt{2q^3}}{(2\pi)^3 \hbar^2} \sum_{i=1}^{2} \sqrt{\frac{m_i^*}{E_{gi}}} L_{Ti} E_i^2 \exp\left(-\frac{a_i}{E_i}\right), \tag{1}$$

where q is the electron charge, $\hbar$ is the reduced Planck constant, m_i^* is the reduced effective mass and E_{gj} is the bandgap width. Fig.1 shows the dependence of the tunnel current on the concentration, we can notice a decrement in the tunnel current under the increment of the concentration.

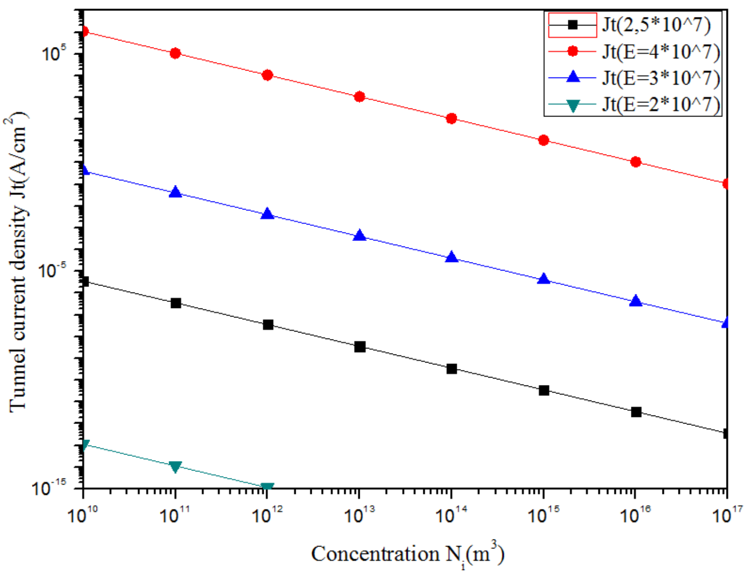

Fig.1. dependence between the tunnel current density and the concentration *N* using different electric fields.

Fig.2 represents the dependence of the tunnel current on the concentration, we can notice the effect of increasing the electric field on the tunneling current.

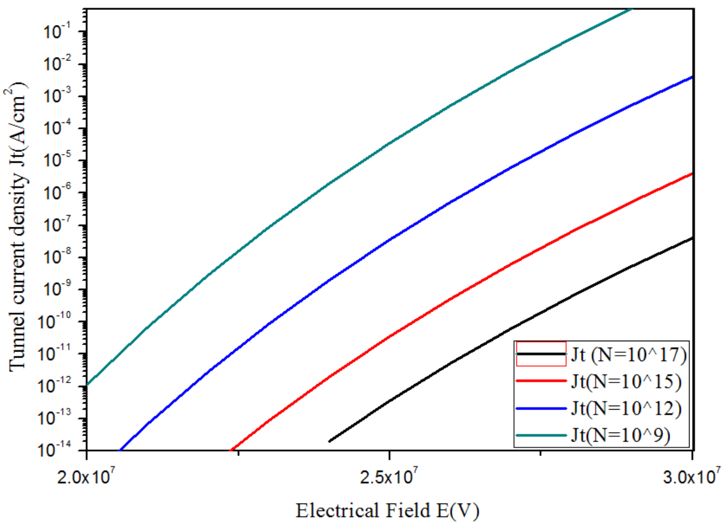

Fig.2. dependence between the tunnel current density and the electric field *E* using different concentrations.

When calculating the parameters of an avalanche photodiode under basic characteristics we should calculate the photosensitivity of the photodiode. Photosensitivity considers the amount to which an object reacts upon receiving photons and it equals $S_I(\lambda) = \lambda^2\pi$. To calculate this characteristic, we need to find the quantum efficiency η of the avalanche photodiode which symbolizes the photon flux that contributes to the photocurrent in a photodiode then we can conduct the noise spectral density [3].

At a specific voltage over the heterostructure we reach a moment where α = β that leads the current photosensitivity $S_I(\lambda)$ to be at its maximum and the effective noise factor reaches its minimum and we can express the noise spectral density by the next formula [3]:

$$S_N = 2qAJ_T M_{ph}^3, \tag{2}$$

M_{ph} is the photocurrent multiplication coefficient which can be calculated by the next expression:

$$M_{ph} = \frac{1-K_0^{-1}}{1-K_0^{\kappa-1}}. \tag{3}$$

In order to be able to calculate M_{ph} K_0 is the ratio of α/β, we also need to find κ which could be calculated by the following relationship [4]:

$$\kappa = \frac{E_1^7 \varepsilon_1^3}{3.19\times10^8 E_{g1}^6} W_1, \tag{4}$$

where W_1 is the QD layer thickness and ε is the material relative permittivity.

The following relationships are fulfilled in the GeSi materials [5]:

$$\alpha_i = \alpha_0 \exp(-\frac{E_{no}}{E}), \tag{5}$$

$$\beta_i = \beta_0 \exp(-\frac{E_{po}}{E}), \tag{6}$$

where $\alpha_0 = 5\cdot10^5$ cm^{-1}, $\beta_0 = 5.6\cdot10^5$ cm^{-1}, $E_{n0} = 0.99\cdot10^6$ V·cm^{-1} and $E_{p0} = 1.32\cdot10^6$ V·cm^{-1} which can be found in the scientific work of Grant [6].

Table 1. Material parameters

	Ge	**Si**	**InP**	**$In_{0.53}Ga_{0.47}As$**
E_g, eV	0.67	1.12	1.34	0.717
ε	16	12	2.35	13.77
m_i^*	0.55	1.08	0.06	0.045

As a result of the calculation a better performance of the GeSi materials was noticeable on several occasions such as: the avalanche photodiodes based on GeSi have shown less values of the tunneling current and higher detectivity under the same conditions comparing to other materials as InP and InGaAs and they also have shown a better quantum efficiency than other materials which make GeSi a better fit to manufacture avalanche photodiodes.

2. Conclusion

To conclude the study discusses the characteristics of an avalanche heterophotodiode based on multilayers of Ge on Si quantum dots with special attention to the tunneling current and the noise spectral density of this photodiode. This brief paper shows the increase of the tunnel current under the effect of the concentration and the electric field and expresses some of the relations used to calculate some of the basic parameters that characterize an avalanche photodiode.

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3. References

[1] Izhnin I.I., Lozovoy K.A., Kokhanenko A.P., Khomyakova K.I., Douhan R.M.H., Dirko V.V., Voitsekhovskii A.V., Fitsych O.I., Akimenko N.Yu., *Appl. Nanosci.*, **12**, 253, 2022; doi: 10.1007/s13204-021-01667-0

[2] Yoshiyuki Hirano, Kenta Okamoto, Susumu Yamazaki, Nobuyoshi Koshida, *Appl. Phys. Lett.*, **95**, 063109, 2009; doi: 10.1063/1.3205119

[3] Burlakov I.D., Filachev A.M., Kholodnov V.A., *J. Commun. Technol. Electron.*, **63**, 1093, 2018; doi: 10.1134/S1064226918090061

[4] Kholodnov V.A., Burlakov I.D., Ilyasov A.K., *J. Commun. Technol. Electron.*, **66**, 362, 2021; doi: 10.1134/S1064226921030104

[5] Ando H., Kanbe H., *Solid-State Electron.*, **24**, 629, 1981; doi: 10.1016/0038-1101(81)90191-X

[6] Grant W.N., *Solid-State Electron.*, **16**, 1189, 1973; doi: 10.1016/0038-1101(73)90147-0