High photoresponsivity of a *p*-channel InGaP/GaAs/InGaAs double heterojunction pseudomorphic modulation-doped field effect transistor

H. J. Kim[a)]
Division of Electronics and Information Technology, Korea Institute of Science and Technology, Cheongryang, Seoul 130-650, Korea

D. M. Kim
School of Electrical Engineering, Kookmin University, 861-1 Junung, Sung-buk, Seoul 136-702, Korea

D. H. Woo, S.-I. Kim, S. H. Kim, J. I. Lee, and K. N. Kang
Division of Electronics and Information Technology, Korea Institute of Science and Technology, Cheongryang, Seoul 130-650, Korea

K. Cho
Department of Physics, Sogang University, Seoul, 100-611, Korea

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In this letter, we report the electrical and optical characteristics of *p*-channel $In_{0.13}Ga_{0.87}As$ double heterojunction pseudomorphic modulation-doped field effect transistor (MODFET) structure grown by gas source molecular beam epitaxy. The Hall mobility and the density of 2-DHGs (two-dimensional hole gases) in the pseudomorphic $In_{0.13}Ga_{0.87}As$ channel were measured to be 250 $cm^2/V\,s$ and $1.9\times10^{12}\ cm^{-2}$ at 300 K, and 5800 $cm^2/V\,s$ and $1.5\times10^{12}\ cm^{-2}$ at 23 K, respectively. The fabricated *p*-channel MODFET shows a good mobility property which is due to high valence band discontinuity of InGaP/GaAs/InGaAs double barriers. The peak energy in the photoluminescence spectrum from the *p*-channel pseudomorphic MODFET structure was found to be 1.4 eV ($\lambda = 881$ nm). The photoresponsivity with this modified pseudomorphic MODFET structure shows outstandingly better than that of a pin photodiode, particularly at low incident optical power. © *1998 American Institute of Physics.* [S0003-6951(98)03505-0]

The optical responses of microwave devices have attracted much interest because of their possible applications to the optoelectronic integrated circuits for detection of high frequency optical signals in the optical communication systems. Recently, the optical response of *n*-channel modulation-doped field effect transistors (MODFETs) have been reported trying to figure out physical mechanisms involved in the photonic microwave characteristics.[1–5] The *p*-channel MODFET performance is generally considered to be poor compared with *n*-channel MODFET due to the higher effective mass and the lower mobility of holes. In addition, the confinement of the 2-DHGs within the quantum wells is less efficient compared to *n*-type structures for two-dimensional electron gases because the valence band discontinuity is usually smaller than conduction band discontinuity.[6,7] In this work, we have fabricated the *p*-channel InGaP/GaAs/InGaAs pseudomorphic MODFET by gas source molecular beam epitaxy (MBE). This modified pseudomorphic double heterostructure, which has a high valence band discontinuity of InGaP/GaAs/InGaAs double heterostructure energy barriers, has been employed to improve electrical and optical properties in the *p*-channel MODFET.

The epitaxial layers for the *p*-channel pseudomorphic MODFET were grown on undoped semi-insulating GaAs substrates by a gas source MBE system. Phosphine (PH_3) gas, arsine (AsH_3) gas, and elemental solid gallium (Ga), indium (In) were used as source materials. Be has been used for the *p*-type dopant in the wide band-gap InGaP acceptor layers. The GaAs buffer layer was grown at the substrate temperature of $T_{sub} = 580\,°C$. The $In_{0.49}Ga_{0.51}P$ epilayer, which is lattice matched to GaAs, was grown at $T_{sub} = 490\,°C$. The growth rates of InGaP and GaAs layers were 1.0 and 0.5 μm/h, respectively. The strained pseudomorphic $In_{0.13}Ga_{0.87}As$ channel layer was sandwiched between two $In_{0.49}Ga_{0.51}P$/GaAs heterojunction barriers expecting better hole confinement and improved transport property. Active layers contributing to the MODFET operation include an undoped GaAs buffer layer of 2000 Å, a *p*-type $In_{0.49}Ga_{0.51}P$ acceptor layer of 100 Å (Be; $2\times10^{18}\ cm^{-3}$), an undoped $In_{0.49}Ga_{0.51}P$ spacer layer of 50 Å, an undoped GaAs layer of 50 Å, an undoped $In_{0.13}Ga_{0.87}As$ channel layer of 100 Å, an undoped GaAs layer of 50 Å, an undoped $In_{0.49}Ga_{0.51}P$ spacer layer of 50 Å, *p*-type $In_{0.49}Ga_{0.51}P$ acceptor layer of 100 Å (Be; $2\times10^{18}\ cm^{-3}$), an undoped wide band-gap $In_{0.49}Ga_{0.51}P$ of 500 Å for a better Schottky barrier, and a heavily doped p^+-GaAs cap layer of 300 Å (Be; $3\times10^{19}\ cm^{-3}$) for improved *p*-type Ohmic contact. This pseudomorphic MODFET structure is expected to have a higher hole concentration and better hole transport property for two-dimensional hole gases in the strained InGaAs channel layer which resulted from the valence band offset between InGaP/GaAs/InGaAs heterojunctions.

The electrical characteristics of the *p*-channel MODFET have been measured by van der Pauw–Hall analysis. The temperature dependence of the electrical properties have been measured using a He-circulated cryogenic cooler. In

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[a)] Electronic mail: khjoel@kistmail.kist.re.kr

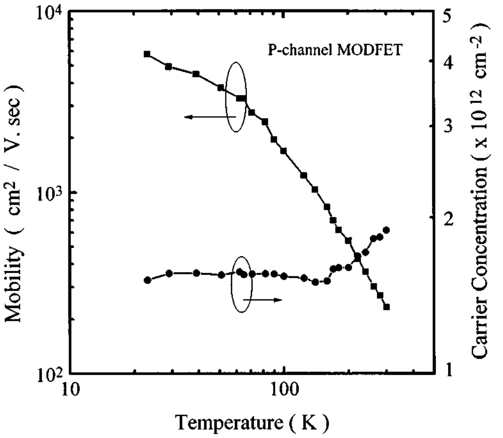

FIG. 1. The temperature dependence of the Hall mobility and the density of the two-dimensional hole gases in the InGaAs channel layer of the p-channel MODFET.

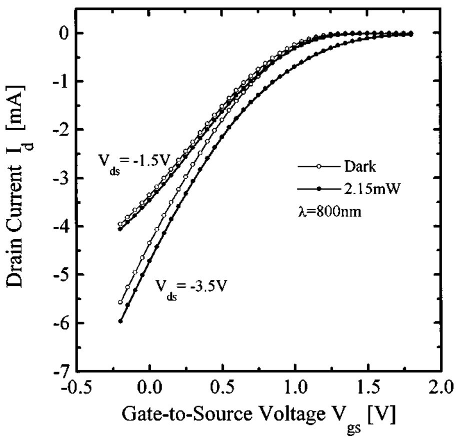

FIG. 3. Measured drain current I_d vs gate-to-source voltage V_{gs} for $V_{ds} = -1.5$ V and -3.5 V at $T = 300$ K. Open circles are measured data without optical illumination while the filled circles with optical input are $P_{\mathrm{opt}} = 2.15$ mW at the end of the optical laser diode module ($\lambda = 800$ nm).

order to measure the electrical transport properties of the two-dimensional hole gas, the p^+-GaAs cap layer was etched away in order to remove parallel conduction during the Hall measurement. Figure 1 shows the temperature dependence of the Hall mobility and the density of 2-DHGs in the p-channel MODFET structure. The mobility and the density of 2-DHGs in the pseudomorphic $In_{0.13}Ga_{0.87}As$ channel were obtained to be 250 cm^2/V s and 1.9×10^{12} cm^{-2} at 300 K, respectively, and 5800 cm^2/V s and 1.5×10^{12} cm^{-2} at 23 K, respectively. The measured mobility of the 2-DHGs in this p-channel MODFET with the modified double heterostructure pseudomorphic InGaAs channel is considerably high even with an extremely high density of 2-DHGs compared to previously reported results.[8]

The photoluminescence measurements were carried out at 10 K using the 6328 Å line of a He–Ne laser with an incident power of 10 mW controlled by an attenuation filter. A 1000 mm focal length spectrometer (resolution 0.2 nm) and a cooled Ge detector were used for the measurement. A photoluminescence spectrum of the grown p-channel MODFET measured at 10 K is shown in Fig. 2. The peak energy of the photoluminescence spectrum appears at 1.4 eV ($\lambda = 881$ nm) and the full width at half maximum (FWHM) is 10.7 meV. When a p-channel MODFET device is optically illuminated by light of energy equal to or greater than the semiconductor band gap, the dominant photoeffects caused by illumination are believed to be a band-to-band photon absorption in the InGaAs channel layer and the two undoped GaAs layers close to the channel.

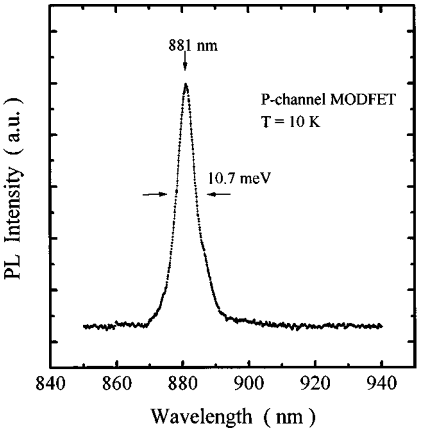

FIG. 2. The photoluminescence spectrum of the p-channel MODFET characterized at 10 K.

The pseudomorphic p-channel MODFET in this work has been made with 1 μm of gate length (L_g), 1.5 μm of gate source (L_{gs}), and 1.5 μm of gate-drain spacings (L_{gd}). We used a π-shaped gate structure with the total gate width (W_g) of 240 μm expecting better optical responsivity from the MODFET. Mesa isolation was accomplished using a wet etching process with AuZn/Cr/Au for Ohmic contact. We also used the selective etching process during gate recess to get better thickness control. The 1 μm gate was formed by photolithography and subsequent evaporation of Ti/Au. The PECVD-grown silicon nitride (1000 Å) was deposited for the passivation of fabricated devices before characterization. For the measurement of the optical characteristics of fabricated $In_{0.49}Ga_{0.51}P/GaAs/In_{0.13}Ga_{0.87}As$ p-channel MODFET, a $\lambda = 800$ nm continuous laser diode source and an HP 4156A semiconductor parameter analyzer have been used. Measured drain current versus gate-to source voltage (V_{gs}) is shown in Fig. 3 for drain-to-source voltage $V_{ds} = -1.5$ V and -3.5 V with and without optical illumination. With optical illumination there is a large change under a large drain voltage for a given V_{gs} while different dependencies on the V_{gs} for a given V_{ds}. This is believed to be due to the photovoltaic effect caused by the optically generated excess carriers in the depletion region of the device. The optical response of the p-channel MODFET is characterized by the photoresponsivity $(R = I_{ph}/P_{\mathrm{opt}})$ which is defined as the ratio of the photocurrent (I_{ph}) to the incident optical power (P_{opt}). The photoresponsivities, as a function of the incident optical power, is shown in Fig. 4 with $V_{gs} = 0$ V and $V_{gs} = 1$ V for the same drain-source voltage $V_{ds} = -3.5$ V. The optical source was routed via an optical fiber (cleaved multimode fiber, minimum illumination diameter of 25 μm, numerical aperture of 0.275) by bringing the fiber end close to the top of the p-channel MODFET so that the light spot covers the full active area of the device (approximately 200 μm in diameter). The incident optical power was equal to the output power from the optical fiber. As expected, the photo-

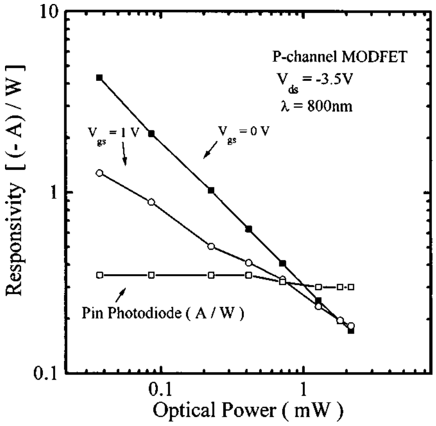

FIG. 4. The p-channel MODFET photoresponsivities as a function of incident optical power with $V_{gs}=0$ V and $V_{gs}=1$ V for the same drain-source voltage $V_{ds}=-3.5$ V measured at $T=300$ K. The data of a pin photodiode are included for comparison.

responsivity of the p-channel MODFET with the modified heterostructure and pseudomorphic InGaAs channel shows huge improvement compared with previously reported results such as a pin photodiode.[2] A significantly high photoresponsivity is obtained at low incident optical power, however it saturates with increasing incident optical power. The difference in the photoresponsivities at $V_{gs}=0$ V and $V_{gs}=1$ V is related to the modulated space charge region under the gate, which makes differences in the current due to optical generation of excess electron-hole pairs with the photovoltaic effect.

In summary, a p-channel $In_{0.49}Ga_{0.51}P$/GaAs/$In_{0.13}Ga_{0.37}As$ pseudomorphic MODFET structure was grown by gas source MBE. Improved electrical and optical characteristics from the p-channel MODFET have been observed mainly due to high valence band discontinuity at InGaP/GaAs/InGaAs double barriers. We also obtained a high mobility of the 2-DHGs with a very high density of the 2-DHGs. The photoresponsivity of the p-channel MODFET was also measured to be significantly high at low incident optical power and showed much better property than that of a pin photodiode. We expect that the p-channel MODFET with an InGaP/GaAs/InGaAs modified heterostructure can be used for the high sensitivity optical detection systems.

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