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GaAs-(AlGa)As Double-Heterostructure Coupled Waveguide Optical Modulator/Switch with Schottky Contact

Kunio TADA, Hideki HAYASHI, Masahiro TSUCHIYA* and Hiroyuki SAKAKI*

Department of Electronic Engineering, University of Tokyo
*The Institute of Industrial Science, University of Tokyo
Hongo 7-3-1, Bunkyo-ku, Tokyo, 113
*Roppongi 7-22-1, Minato-ku, Tokyo, 106

The GaAs-(AlGa)As double-heterostructure (DH) coupled-waveguide optical modulator/switch with Schottky contact has been analyzed, which is expected to be fabricated more easily than the DH device with pn junction without degrading the modulation characteristics. Actual devices have been fabricated on an MBE grown wafer. The extinction ratio of 12dB has been obtained at the switching voltage of 16V at 1.06μm wavelength, and a cutoff frequency of 1.5GHz has been measured.

§1. Introduction

The coupled-waveguide optical modulator/switch, which is an electrically switched optical directional coupler, is one of the most important components in guided-wave and integrated optics. This type of device was first realized under a GaAs multilayered planar waveguide configuration[1]. Several device structures under the channel waveguide configuration for GaAs-based or InP-based semiconductors have been devised so far[2-17]. Recently we proposed a GaAs-based double-heterostructure (DH) device with Schottky contact[14]. In this paper we report the modulation characteristics of the fabricated device.

§2. A DH device with Schottky contact

Among various semiconductor coupled-waveguide optical modulators under the channel waveguide configuration, a DH device with pn junction is expected to have the lowest modulating voltage and modulating power per bandwidth $P/\Delta f$ because of the most efficient overlap of the modulating electric field with the optical field[4,14]. However, this device has following difficulties;

1) It is necessary to control the height of the strip waveguide very accurately.
2) If the ohmic contact resistance between the top metallic electrode and the p^+-(AlGa)As layer is high, degradation of high-frequency response is caused[15,18].

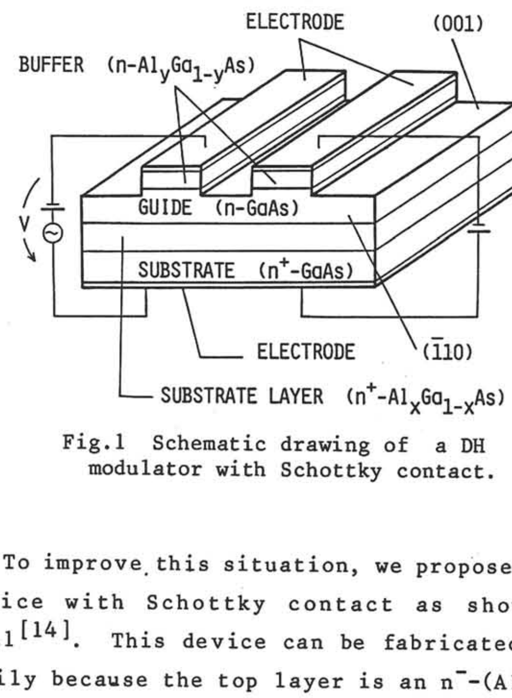

Fig.1 Schematic drawing of a DH modulator with Schottky contact.

To improve this situation, we proposed a DH device with Schottky contact as shown in Fig.1[14]. This device can be fabricated more easily because the top layer is an n^--(AlGa)As rather than the p^+-(AlGa)As. The depletion region spreads also into the buffer layer, so the switching voltage is slightly higher than that of a DH device with pn junction. However, the high-frequency response is expected to be superior to that of a DH device with pn junction because of the thick depletion region and the negligible contact resistance.

This device was analyzed by applying the equivalent refractive-index method[19,20], and the dependence of its characteristics on device parameters was studied. An example of the results

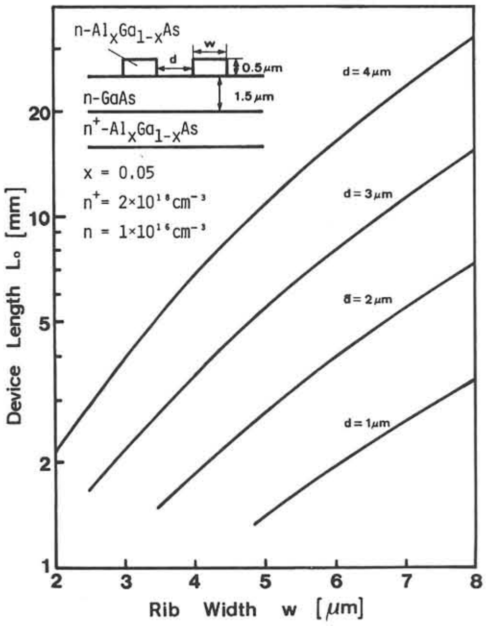

Fig.2 Calculated coupling length vs. width of the rib waveguide with guide spacing as parameter.

Table I Design example of a DH device with Schottky contact.

x (= y)	0.13	0.13	0.13
n^+ [cm^{-3}]	2×10^{18}	2×10^{18}	2×10^{18}
n [cm^{-3}]	1×10^{16}	1×10^{16}	1×10^{16}
Guide Thickness [µm]	1.5	1.5	1.5
Buffer Thickness [µm]	0.5	0.5	0.5
Rib Width [µm]	4.0	4.0	4.0
Rib Spacing [µm]	4.0	4.0	4.0
Rib Height [µm]	0.45	0.50	0.55
Device Length [mm]	4.3	5.9	8.4
Switching Voltage [V]	21.7	15.9	12.4
Capacitance [pF]	1.3	1.6	2.2
P / Δf [µW/MHz]	233	160	130
Δf (50Ω) [GHz]	5.1	3.9	2.9

is shown in Fig.2. A design example is shown in Table I.

§3. Fabrication

Following three layers were grown by MBE technique on an n^+-GaAs substrate ($n=2.5\times10^{18}$ cm^{-3}); an n^+-(AlGa)As substrate layer ($n=2\times10^{18}$ cm^{-3}, 2µm thick), an n-GaAs guide layer ($n=1\times10^{16}$ cm^{-3}, 1.5µm thick) and an n-(AlGa)As buffer layer ($n=1\times10^{16}$ cm^{-3}, 0.5µm thick). For the growth of two $Al_xGa_{1-x}As$ layers, the superlattice structure was adopted to obtain an accurate control of a low Al content,x. The well (GaAs) width and the barrier ($Al_{0.46}Ga_{0.54}As$) width were 55Å and 20Å, respectively, which then gave the mean Al content x of 0.12. Photoluminescence of the wafer at 77K showed a peak (λ=0.74µm) corresponding to the spectrum of $Al_{0.13}Ga_{0.87}As$.

After evaporating Au-Ge-Ni on the bottom surface of the wafer, it was annealed in N_2 atmosphere at 440°C in order to obtain an ohmic contact. After evaporating Al on the top surface (0.2µm thick) and exposing OFPR-800 photoresist, the rib waveguides were formed by etching Al in H_3PO_4 and (AlGa)As in H_3PO_4-H_2O_2-H_2O etchant. The sample was cleaved and mounted on a partially Au-metallized ceramic stem. The bonding pad on the sample and the Au electrode of the ceramic stem were cennected by the Au bonding wire.

The breakdown voltage of a sample whose rib waveguide width, spacing and height were 4µm, 4µm and 0.5µm, respectively, was 19V. Micrographs of the sample are shown in Fig.3.

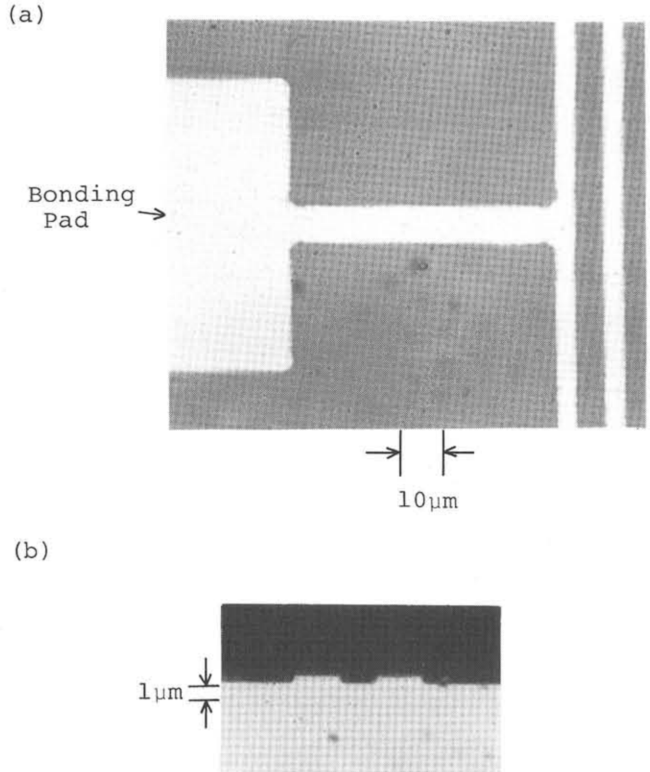

Fig.3 Micrographs of the sample. (a) Top view and (b) cross section.

§4. Modulation characteristics

The switching characteristics of the above-mentioned sample with a length of 4.4mm was measured at 1.06μm light wavelength using the end-fire coupling technique. A CW single-mode Nd:YAG laser beam was focused by an objective lens on the cleaved input face of a rib waveguide to excite the TE_0-like mode. The output beams were magnified by an objective lens and detected by a Si photodiode.

The measured variation in optical power output from each waveguide is plotted in Fig.4 as a function of applied dc reverse voltage. I_1 and I_2 are the output optical powers from the input-side guide and the coupled-side guide, respectively. The solid lines are the theoretical values calculated from the actual device parameters. The difference between the measured and calculated values at voltages higher than 15V is thought to be caused by the increased reverse current. The extinction ratio of 12dB was measured at 16V. The total insertion loss was 24dB.

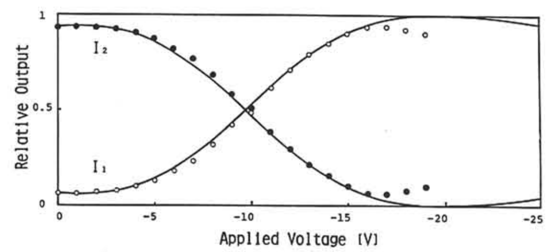

Fig.4 Output power vs. applied dc reverse voltage.

The setup for measuring high-frequency modulation characteristics is illustrated in Fig.5. The stem on which the sample was mounted was fixed on a strip line. The optical power output was detected by a Si-APD.

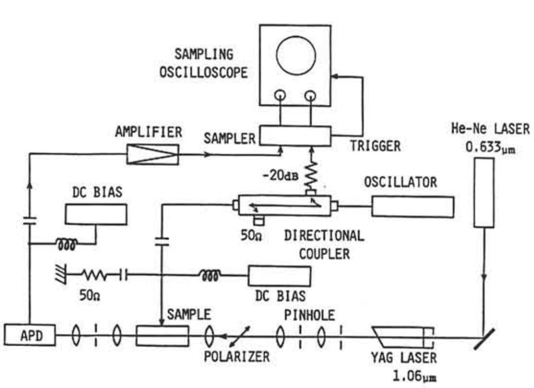

Fig.5 Setup for measuring high-frequency modulation characteristics.

Measured modulation degree for a sinusoidal signal of $1V_{p-p}$ and a bias of 10V is plotted in Fig.6 as a function of the modulating frequency. The 3dB cutoff frequency Δf is measured as 1.5GHz.

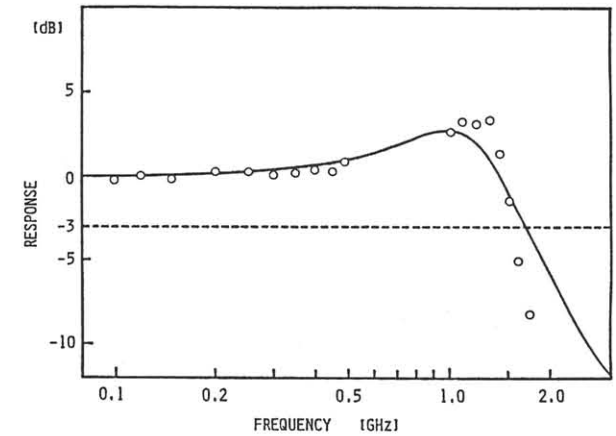

Fig.6 Measured modulation degree vs. modulating frequency.

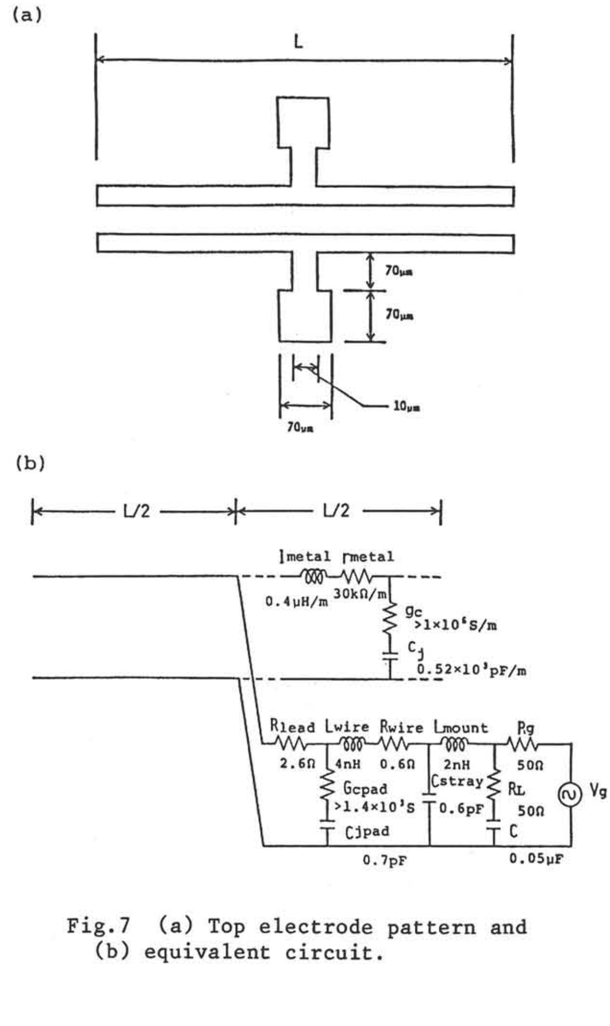

Fig.7 (a) Top electrode pattern and (b) equivalent circuit.

The solid line indicates the theoretical value computed from an equivalent circuit with distributed constants along the optical waveguide and other parasitic elements in and around the sample as shown in Fig.7(b). This figure reflects the shape of the top electrode as shown in Fig.7(a). The measured and calculated values are in fairly good agreement.

We studied the calculated high-frequency characteristics, and it turned out that the inductance of the bonding wire L_{wire} and the series resistance of the waveguide electrode per unit length r_{metal} had influences on the high-frequency characteristics remarkably. If L_{wire} is reduced to half, the high-frequency response can be improved from the curve A' to the curve B in Fig.8. Further, by thickening the Al electrode by three times (0.6 μm thick) to reduce r_{metal}, the curve C is obtained. The curve D is the ideal case without all the parasitic elements except the junction capacitance per unit length c_j and the bonding pad capacitance C_{jpad}. The frequency response of several GHz will be obtained if we utilize an advanced technology being used for electrodes and mountings of GaAs MESFETs etc.

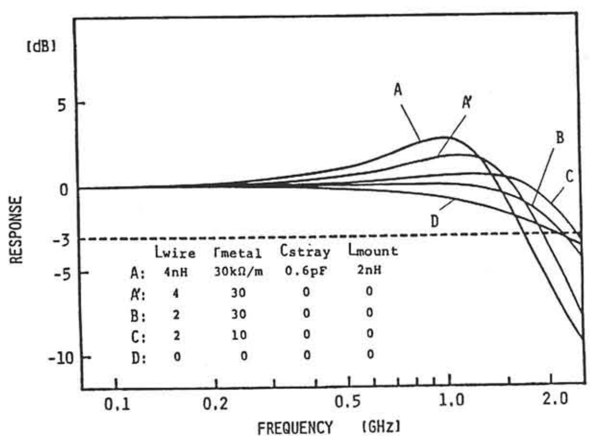

Fig.8 Calculated modulation degree vs. modulating frequency.

§5. Conclusion

A GaAs-(AlGa)As double-heterostructure coupled-waveguide optical modulator/switch with Schottky contact is analysed and it is shown that this device with the merit of easier fabrication has good modulation characteirstics standing comparison with a DH device with pn junction. The device was fabricated on an MBE grown wafer. The extinction ratio of 12dB was obtained at the switching voltage of 16V at 1.06 μm wavelength and a cutoff frequency of 1.5GHz was measured. A higher cutoff frequency would be obtained if the inductance of the bonding wire and the resistance of the Al electrode were further reduced.

Acknowledgements

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