METAL–INSULATOR–SEMICONDUCTOR LIGHT MODULATORS UTILIZING
THE FRANZ–KELDYSH EFFECT IN GALLIUM ARSENIDE

A. N. Blagodarov, V. D. Zhuravov, I. V. Kochnev,
V. Ya. Kunin, S. F. Morozov, A. V. Rodionov,
and V. I. Fomichev

A study was made of the electroabsorption kinetics, as well as of the spectral and field dependences of the contrast and efficiency of modulation of light in Al–SiO₂–GaAs–n⁺-GaP structures near the fundamental absorption edge of GaAs (875–910 nm). Values of the contrast amounting to 10⁻¹² and the modulation efficiency of 30–40% were achieved. It was demonstrated that optical data storage was possible with the aid of an He–Ne laser. Optical memory was observed in Al–SiO₂–(n–n⁺)-GaAs structures on application of voltage pulses causing carrier accumulation; the effect was due to the capture of electrons at the SiO₂–GaAs interface. The absorption edge of epitaxial GaAs films on GaP substrates had an exponential profile in the photon energy range 1.37 ≤ hν ≤ 1.40 eV in fields 0 ≤ E ≤ 6.5·10⁴ V/cm. An empirical relationship was obtained for the spectral and field dependences of the absorption coefficient.

The greatest difficulties in the practical implementation of optical data processing devices are encountered in the input of the analyzed and analyzing functions into an optical processor. A promising way of solving these difficulties is provided by the use of controlled transparencies [1]. One of the physical mechanisms which can be used in the construction of controlled transparencies is the electroabsorption near the fundamental band edge, known as the Franz–Keldysh (FK) effect [2, 3]. Interest in this effect has recently increased because of the developments in integrated optics, which have led to the demand for methods and devices capable of modulating the intensity of light in a wide range of modulation frequencies but requiring only a small modulation energy [4].

Unfortunately, the published information on the practical aspects of direct modulation of the intensity of light and in particular on the use of the FK effect [5–8] is very limited compared with the large amount of information on the phase modulation of light.

We shall consider the possibility of constructing a light modulator which utilizes the FK effect in an epitaxial GaAs film which is the semiconductor layer in a metal–insulator–semiconductor (MIS) structure. This material was selected because one can then use commercially available lasers and light-emitting diodes made of GaAs–Ga₂Al₁₋ₓAs heterostructures as sources of the readout light (see, for example, [9]).

There was also an additional interest in the utilization of the accumulation of charge carriers at the insulator–semiconductor interface for the purpose of optical storage [10].

1. Samples and Measurement Method

Epitaxial GaAs films were grown by the chloride method on low-resistivity substrates of two types: n⁺-type GaAs (n ≈ 10¹⁸ cm⁻³) and n⁺-type GaP (n ≈ 10¹⁷ cm⁻³) oriented in (100) planes. The substrate temperature during the deposition was 730°C and the rate of deposition was 0.2–0.3 μ/min. The electron density in the epitaxial layer of (n–n⁺)-GaAs (type I) structures was (1–5)·10¹⁴ cm⁻³, whereas the corresponding density in GaAs–n⁺-GaP (type II) structures was 10¹²–10¹³ cm⁻³ in the case of partial compensation, which was clearly due to misfit dislocations at the gallium phosphide–arsenide interface.

Films of SiO₂, ~2 000 Å thick, were deposited on the surfaces of epitaxial structures by a plasma-chemical method at temperatures 280–300°C. A semitransparent aluminum electrode was evaporated on top of the silicon oxide film and an ohmic contact with the substrate was formed by alloying with tin by the electric

The absorption of the readout light in the $n^+$-type GaAs substrate was reduced by electrochemical etching of a window in the substrate; the diameter of the window was 0.5-1.0 mm. The electroabsorption signal, representing the change in the optical transmission $\Delta T$ in an electric field, was displayed on the screen of an oscilloscope when a structure was subjected to rectangular voltage pulses (up to 160 V) of different polarities. The duration of the pulses was varied within the range $10^{-7}$-$10^{-4}$ sec. An FEU-62 photomultiplier was used as the detector.

The transmission spectra of the samples were recorded using a MDR-2 monochromator; this was done in the wavelength range 875-910 nm with a resolution 2 nm. The intensity of the readout light was $\approx 10^{-4}$ W/mm$^2$. All the measurements were carried out at room temperature.

An analysis of the capacitance-voltage characteristics of type I structures indicated the presence of a high density of surface states ($\approx 10^{13}$ cm$^{-2}$·eV$^{-1}$) in the upper half of the band gap at the SiO$_2$-GaAs interface. When the rate of change of the depletion-inducing bias voltage was sufficiently slow ($\approx 1$ V/sec), these states did not reach the state of inversion in a structure so that the surface potential had a depletion-type value ($\psi_s \approx 0.25$ eV). When the rate of change of the voltage was increased, a nonequilibrium depletion regime was established in the structure because the charge in the surface states could not follow changes in the charge on the metal electrode.

In the case of type II structures the capacitance measured at 1 MHz was independent of the bias voltage and was equal to the geometric capacitance of the epitaxial GaAs film. This was due to the fact that the high-resistivity ($n \approx 10^{12}$-$10^{13}$ cm$^{-3}$) GaAs film was completely depleted of carriers and the application of an hf or pulsed voltage made this film behave as an insulator with two blocking electrodes.

2. Results of Measurements and Discussion

2.1. Kinetics of Changes in the Electroabsorption Signal. Figure 1 shows the change in the absorption ($\Delta T$) in epitaxial GaAs films under the action of voltage pulses of different polarities and durations applied to different MIS structures. We shall assume that the polarity of the pulse is identical with the sign of the potential on the aluminum electrode.

When a structure of type I is subjected to short ($\tau_p \leq$ msec) negative voltage pulses, the electroabsorption signal repeats the shape of the voltage pulses. An increase in the duration of the voltage pulses to several tens of milliseconds makes it possible to observe relaxation of the electroabsorption signal to zero with a characteristic time $\tau_1 \approx 20-30$ msec. The value of $\tau_1$ is inversely proportional to the intensity of the readout light. This indicates that thermal generation of carriers in GaAs has a negligible effect on the relaxation of the electroabsorption signal.

Application to the same structure of positive pulses of any duration ($\tau_p \approx 10^{-7}$-$10^{-4}$ sec) produces the electroabsorption signal only at the trailing edge of the pulse; the amplitude and relaxation time are the same as in the preceding case (Figs. 1a and 1b). This effect can be regarded as optical memory observed when positive pulses are used. The memory time $\tau_m$ can be assumed to be 2 msec, because in this time the value of $\Delta T$ decreases by 10% ($\tau_m \approx 0.1\tau_1$).

This optical memory is observed in autoepitaxial structures with doped ($n \approx 10^{15}$ cm$^{-3}$) and high-resistivity compensated ($n \approx 10^{13}$ cm$^{-3}$) epitaxial GaAs films.

We shall now consider the optical memory mechanism. The application of a positive pulse resulted in the accumulation of electrons and their capture by traps at the SiO$_2$-GaAs interface. (In the case of high-resistivity GaAs, electrons are injected from the substrate.) These electrons screen the semiconductor from the electric field and the electroabsorption signal is not observed. At the end of a positive pulse the negative charge accumulated at the interface induces an electric field in the GaAs film and it is this field that produces the electroabsorption signal. As the trapped electrons are liberated, the transmission relaxes to its initial value. The strong dependence of the relaxation time of the electroabsorption signal on the intensity of light shows that the liberation of the trapped electrons occurs by way of their recombination with holes generated by the readout light.

In type II structures the shape of the electroabsorption signal is the same for negative and positive voltage pulses (Figs. 1c and 1d). In the case of long pulses ($\tau_p \geq 100$ msec) the initial reduction in the transmission is followed by relaxation of $T$ to the initial value at a rate characterized by a time constant similar to that of type I structures ($\tau_1 \approx 30-50$ msec). The fall of the transmission to zero after the end of