Ultrafast magnetophotoconductivity of semi-insulating gallium arsenide

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(Received 13 November 1980; accepted for publication 18 May 1981)

The speed of opto-electronic switches is increased or decreased by the application of a magnetic field. This is achieved by inducing a carrier drift toward or away from the semiconductor surface, resulting in the enhancement or suppression of surface recombination. We establish that surface recombination plays a major role in determining the speed of the opto-electronic switch.

PACS numbers: 72.40. + w, 72.20.Jv, 78.20.Ls, 73.25. + i

Fast photoconductive switches have been investigated by a number of experimenters.[1-3] The primary objectives in these efforts have been the production of ultrafast current pulses (for Pockels-cell triggering, etc.), the demonstration of these switches as fast photodetectors, and the determination of the photocarrier recombination properties of the materials used. We have observed response times as short as 70 psec for Cr:GaAs switches illuminated by picosecond optical pulses. The fast response of Cr:GaAs has been attributed to the presence of chromium recomination centers in the semiconductor.[3] However, it is necessary to consider the effects of surface recombination in order to adequately understand the operation of the opto-electronic switch.

It is impossible to determine both surface and bulk recombination parameters from the switch response time alone. A broad range of combinations of these two parameters will generate a given pulsewidth. Figure 1 shows lines of constant pulsewidth full width at half maximum (FWHM) in the two dimensional space of surface recombination velocity and bulk carrier lifetime. These curves are generated from Eq. (3) below, with $B = 0$, and represent the output from an infinitely fast detection system. There is clearly an indeterminacy of the two recombination parameters, S and τ, when only the output pulsewidth of the switch is known. It is necessary to decouple the contributions of the two recombination phenomena in order to determine either parameter accurately. This can be accomplished through the application of a magnetic field.

Magnetophotoconducitivity measurements are taken using the geometry shown in Fig. 2. Metallic contacts on a Cr:GaAs chip are separated by a gap. A voltage V is applied to the contacts, but negligible current flows across the highly resistive gap. A 1-2-psec light pulse is directed onto the gap, and the resulting electron-hole pairs allow current to flow for the duration of their existence. If a magnetic field B is applied in the z direction, both electrons and holes (bearing opposite charges and traveling in opposite directions) are drawn either toward or away from the surface, depending on the sign of the magnetic field. In addition to the omnipresent bulk recombination, if carriers are drawn toward the surface, more of them experience surface recombination as well. The effect is to decrease the overall carrier lifetime, which speeds up the temporal response of the switch. The opposite sign of the magnetic field drives carriers into the bulk, prolonging the life of the carriers and slowing the switch response.

Assuming no carrier density dependence in the x or z directions, we write a diffusion equation for the carrier density n

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial y^2} - \frac{n}{\tau} + \mu^2 EB\frac{\partial n}{\partial y},$$

which includes the effect of the transverse (y) particle current density $-n\mu^2 EB$ due to the magnetic field. Here we have also assumed that ambipolar diffusion is established rapidly due to the high excitation level.

We need to solve (1) subject to the initial and boundary conditions

$$\begin{aligned} &n(t=0) = n_0 e^{\alpha y}, \\ &n(y=\infty) = 0, \\ &\frac{D\partial n}{n\partial y}\Big|_{y=0} = S - \mu^2 EB, \end{aligned} \tag{2}$$

the last of which equates the total current density flowing into the surface to the recombination rate nS per unit area. Here α is the absorption coefficient, S is the surface recombination velocity, D is the ambipolar diffusion coefficient, τ is the bulk recombination lifetime, and μ is the carrier mobility.

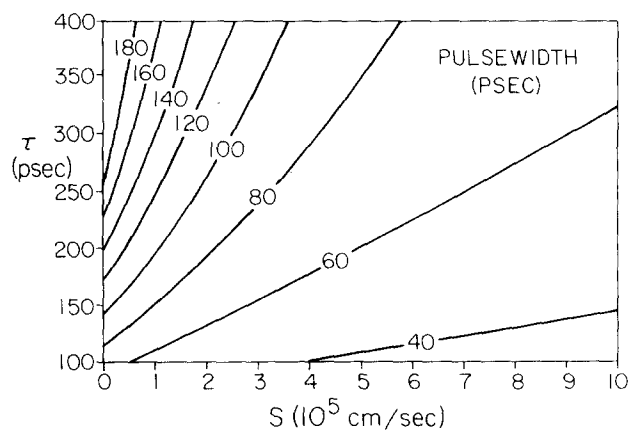

FIG. 1. Lines of constant FWHM pulsewidth plotted against the bulk recombination lifetime τ and the surface recombination velocity S. These values must be convoluted with the detection system response to obtain the expected observed pulsewidth.

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 0003-6951/81/150266-03$00.50

$$i(t) \propto \int_0^\infty n(y,t)dy = \frac{n_0 \exp\left[-(t/\tau) - k^2 Dt\right]}{\alpha(k-\beta)(\gamma-\beta)(k-\gamma)}$$

$$\times \left[k(\beta^2-\gamma^2)W(k\sqrt{Dt}) + \beta(\gamma^2-k^2)W(\beta\sqrt{Dt})\right.$$

$$\left. + \gamma(k^2-\beta^2)W(\gamma\sqrt{Dt})\right]. \quad (3)$$

In our experiment the switch was illuminated with 1-nJ 6100-Å psec pulses from a mode-locked dye laser. Chromium contacts were evaporated onto the Cr:GaAs chip, which was then mounted on a stripline. The chip was bonded to the stripline with conductive epoxy instead of solder. This was done to preserve surface preparation by avoiding thermally enhanced surface reactions between the GaAs and the adsorbed impurities. The lower conductivity increased the detection system rise time to approximately to 60 psec, but the magnetophotoconductive phenomena were still clearly observed. (Switches of different construction do have a scope-limited rise time.[4]) Chromium was selected for the contact material owing to its good adhesion without alloying. Although we have not verified whether this provided ohmic contacts, chromium contacts passed several times more current than any of the other metal contacts investigated, including Au, Au-Zn, Au-Sn, Au-Ge, and In. A typical method of contact application involves a metal etch to produce the gap in the evaporated contacts. We found that this etch frequently eradicated prior surface preparations of the Cr:GaAs. In order to avoid this effect, we evaporated the metallic contacts onto the chip using a 75-μ wire to mask the gap. An electric field of 4×10^3 V/cm and a magnetic field of 15 kG were applied to the chip. The fast current pulses were detected with a 25-psec rise-time sampling oscilloscope, and the output signals from the oscilloscope were loaded into a multichannel signal averager. These signals were recorded on magnetic tape for digital processing and curve fitting.

The left trace of Fig. 3 shows a current pulse obtained under the application of a magnetic field to drive the carriers away from the surface; the right trace was obtained with the magnetic field in the opposite direction. The difference in pulsewidth demonstrates the effect of the magnetic field on the overall photocarrier lifetime. The height difference between the pulses is due to the finite bandwidth of the system; the initial amplitudes of the undispersed pulses should be the same. In this case, the surface of the gallium was prepared with a passivating (small surface recombination) citric

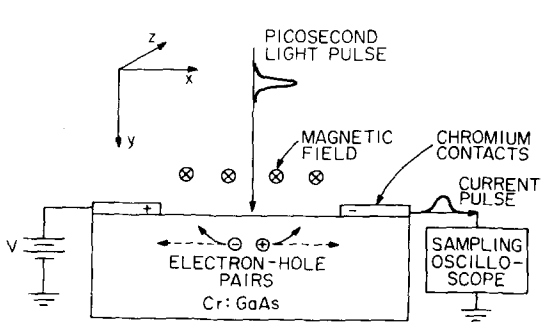

FIG. 2. Geometry for magnetophotoconductivity measurements.

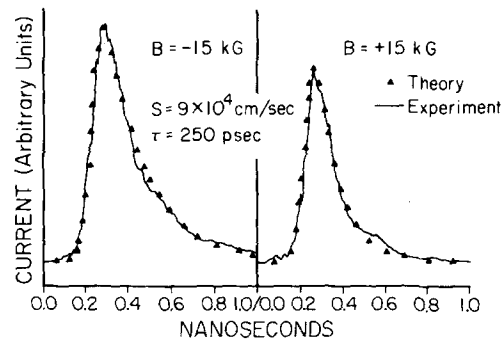

FIG. 3. Magnetophotoconductivity of a passivated Cr:GaAs surface. Left trace: carrier drift into bulk. Right trace: carrier drift toward surface.

acid etch.[5] Figure 4 shows the data obtained from a gallium arsenide surface wich was activated (large surface recombination) through mechanical polishing. Note the greater effect of the magnetic field on the response of the Cr:GaAs sample with the higher surface recombination velocity. Superimposed on the experimental traces are symbols showing the theoretical curve (3) passed through a 60-psec Gaussian filter, with the parameters of surface and bulk recombination determined through a nonlinear least-squares-fitting routine. Using the values $\alpha = 4.3\times10^4$ cm^{-1}, $\mu = 3\times10^3$ cm^2/V sec, and $D = 8.2$ cm^2/sec, the best fit bulk recombination lifetime was determined to be 250-psec in both cases, while the surface recombination velocities were found to be 9×10^4 and 7.5×10^5 cm/sec in Figs. 3 and 4, respectively. The bulk value was in good agreement with that obtained from high-intensity cw illumination experiments.[6] The surface recombination velocities also show good agreement with data obtained from luminescence experiments. The luminescence data of Ref. 5 yield values of S that were 5×10^4 and 10^6 cm/sec, respectively, for the same passivating and activating surface preparations used in our experiment.

Another phenomenon, the ultrafast photomagnetoelectric effect, was observed in the absence of an applied electric field. This gave rise to extremely short current pulses which surpassed the resolution limit of our system. These pulses, resulting from the initial diffusion of carriers into the bulk of the Cr:GaAs in the applied magnetic field, had predicted pulse pulsewidths of ~5 psec.[7] Such short pulses may be useful as high temporal resolution probes in fast current pulse correlation experiments.[8]

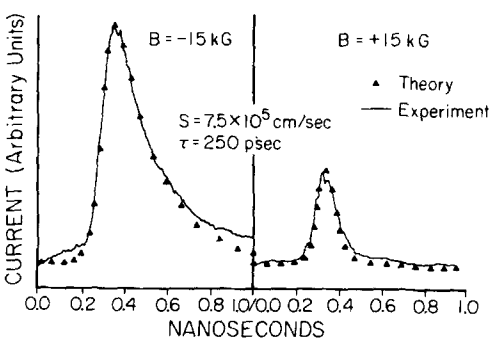

FIG. 4. Magnetophotoconductivity of an activated Cr:GaAs surface. Left trace: carrier drift into bulk. Right trace: carrier drift toward surface.

Our magnetophotoconductivity results conclusively demonstrate the significant contribution of surface effects on the speed of Cr:GaAs opto-electronic switches. This measurement technique offers a means of simultaneously determining the surface recombination velocity and bulk recombination lifetime of transiently generated photocarriers.

This work was supported by a National Science Foundation Grant and a National Science Foundation Graduate Fellowship (T.L.K.).

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50-nm silicon structures fabricated with trilevel electron beam resist and reactive-ion etching

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(Received 17 April 1981; accepted for publication 19 May 1981)

A trilevel electron beam resist has been used to make 25-nm metal features on thick silicon substrates. Using this metal as a mask for reactive ion etching, silicon structures 0.33 μm deep have been fabricated. The resist consists of a thin upper layer of polymethylmethacrylate (PMMA), a middle layer of Ge, and a lower layer of co-polymer of methylmethacrylate and methacrylic acid, P(MMA/MAA). High-resolution patterns are written in the upper resist layer and are transferred to the lower layers by reactive-ion etching. Completed resist stencils have 300-nm high walls with near-vertical profiles and are suitable for liftoff processing.

PACS numbers: 85.40.Mt, 41.80.Dd, 79.20.Nc

Although conventional electron beam lithography can be used to make features as small as 100 nm on thick silicon substrates, this resolution can only be obtained using a thin resist layer which is of limited utility as an etch mask or liftoff stencil. This limitation results from electrons which forward scatter in the resist and backscatter from the substrate.[1,2]

A structure which reduces scattering effects and allows high resolution fabrication is a thin resist film on a thin, low atomic number substrate. AuPd lines, 25 nm wide on 50-nm centers, have been made on a 60-nm-thick Si_3N_4 substrate by ion milling through a 110-nm-thick polymethylmethacrylate (PMMA) mask.[3] Though important for fundamental studies, the restriction to membrane substrates limits the usefulness of this process for device fabrication. Patterns with comparable resolution can be made on thick substrates by separating the thin layer of high-resolution resist from the substrate by a layer of more electron sensitive resist.[4] Upon development, a high resolution pattern is obtained in the upper layer. A wider pattern is developed in the lower layer, resulting in undercut resist profiles. Not only does this technique reduce the effects of scattering, but the resulting resist profiles are well suited to liftoff processing or oblique fabrication techniques.[5] Au lines, 40 nm wide on 80-nm centers,[4] and superconducting tunnel junctions, 100 nm square,[6] have been made this way. The presence of an undercut (~200 nm) in the lower layer, however, imposes limitations on the spacing and shape of adjacent features.

We report here results obtained with a trilevel resist system which yields 25-nm resolution in resist patterns having nearly vertical profiles. The completed resist pattern can be used either as a thick etch mask or as a liftoff stencil. Trilevel resist systems have previously been used to pattern uniform lines on topographically rough substrates[7] and to form *in situ* x-ray masks for the fabrication of high aspect ratio resist patterns having submicron features.[8,9] Our work investigates the use of trilevel resist for forming very fine features.

The upper resist layer is 950 000-mol wt polymethylmethacrylate (PMMA), a standard high-resolution electron beam resist.[10] A 100-nm film is formed by spin coating at 8000 rpm using a 3-wt % solution in chlorobenzene. The lower layer is a 280 nm thick film of a co-polymer of 90.8% (by weight) methylmethacrylate and 9.2% methacrylic acid, P(MMA/MAA),[11] formed by spin coating a 7.6-wt % solution in acetic acid at 8000 rpm. This material adheres well to the Si substrate, and the overlying Ge layer adheres well to it. It also has a glass temperature that is higher than that of

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