Photovoltaic transistors based on a steady-state internal polarization effect in asymmetric semiconductor superlattices

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(Received 5 March 1991; accepted for publication 22 April 1991)

In semiconductor superlattices lacking the reflection symmetry, transient internal polarization fields have previously been reported. We show that a modified structure can generate a steady-state photovoltage. We then propose a new class of photovoltaic transistors in which this voltage directly controls the conductivity of the transistor channel.

In recent years, there has been a growing need for optoelectronic integrated circuits in optical communication systems. One particular interest in this context is the development of receivers. A number of schemes have been reported[1] for the integration of a photodiode with a field-effect transistor (FET). In these schemes, the electron hole pairs, generated by light, recombine through external circuits giving rise to a photocurrent. The photocurrent, passed through an external resistor, modulates the voltage that is supplied to the gate of a FET. To our knowledge, there exist no monolithic devices that directly utilize a "photovoltage" to control the FET gate. In this letter we wish to propose a new class of devices, whose key novelty is such a photovoltaic transistor (PVT) aspect.

Our idea of the PVT arises from the well known fact that the threshold voltage of a FET depends on the charge distribution inside the gate insulator.[2] The proposed device is based on a photovoltaic phenomenon unique to semiconductor heterostructures lacking the reflection symmetry. A transient version of this phenomenon has been observed by Capasso *et al.*[3] in a sawtooth superlattice implemented in the graded GaAs/AlGaAs heterostructure system. That structure, however, did not generate an observable steady-state photovoltage. As shown below, and will be discussed in detail elsewhere,[4] the absence of a steady-state effect can be explained by the fact that the minority-carrier lifetime τ_e was too long.

In structures with a short τ_e, a steady-state photovoltage can be generated. A variety of asymmetric superlattices can be used. Here, we shall illustrate the physics with a particular design, shown in Fig. 1. Layers *a*, *b*, and *d* in the figure can be implemented, for example, with *p*-doped InGaAs, InAlAs, and InP, respectively. Because of the *p*-type doping, the valence band is effectively tied to the equilibrium Fermi level E_F, while the conduction-band edge profile contains a step between the *a* and *d* layers, corresponding to their energy gap difference ΔE_g.

Under illumination with the photon energy above the energy gap in layer *d*, the electron-hole pairs are generated in both layers with an approximately uniform rate $\alpha\Phi$, where α is the absorption coefficient and Φ the incident photon flux. Photogenerated minority carriers will redistribute between layers *d* and *a* prior to the recombination. We can estimate the time period Δt required for the electrons to diffuse across layer *d* as $\Delta t \sim d^2/D_n$, where D_n is the electron diffusivity. For $D_n \approx 250$ cm^2/s (corresponding to a minority-carrier mobility of 10 000 cm^2 V^{-1} s^{-1}) and $d \approx 1000$ Å, this time is well below 1 ps. For $\Delta t \ll \tau_e$, we can assume that electrons establish a quasiequilibrium between layers *a* and *d* such that the electron volume densities in these layers are approximately related by the Boltzman factor $\exp(\Delta E_g/kT)$. Therefore, the recombination will mainly occur in layer *a* and an internal current J_n will be established to maintain the quasi-equilibrium condition by injecting electrons from layer *d* to layer *a*. This current is directly proportional to Φ:

$$J_n \approx e\alpha\Phi d. \tag{1}$$

In a steady state, the net current density must vanish, and hence $J_p = J_n$, where $J_p = ep\mu_p E$ is the hole current den-

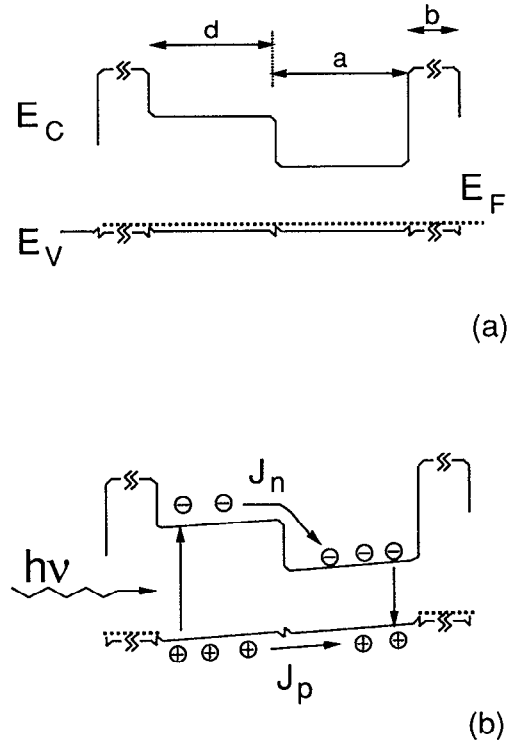

FIG. 1. The energy band diagram in one period of an asymmetric superlattice in thermal equilibrium (a) and under illumination (b).

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sity and p and μ_p are the hole concentration and mobility, respectively. The driving field E is the photopolarization field. The energy band diagram under illumination is shown in Fig. 1(b). Electrostatically, E is produced by a local unbalance between the densities of charges due to the photogenerated electrons n and the excess holes $p-p_0$, where p_0 is the hole concentration provided by the doping.

The steady-state photovoltage V across N cascaded periods of the structure can be approximated by

$$V \sim NEd \sim \frac{d}{2p\mu_p}\frac{I_L}{h\nu}, \tag{2}$$

where $I_L = h\nu\Phi$ is the radiation power intensity and $h\nu$ is the photon energy. This estimate assumes that the total length of the superlattice has been optimized, $N\alpha(a+d)\sim 1$, and that $a \approx d$. We see that V can be enhanced by increasing d or decreasing the hole conductivity. If we take $I_L = 10^4$ W/cm^2, and $h\nu = 0.95$ eV (corresponding to $\lambda = 1.3$ μm), V will be over 0.3 V for $d = 1000$ Å, assuming $p = p_0 = 10^{16}$ cm^{-3} with $\mu_p = 100$ cm^2/V s.[5]

In these estimates, we have assumed that $\alpha\Phi\tau_e \ll p_0$ and, therefore, p is dominated by the doping. At $I_L = 10^4$ W/cm^2 and $p_0 = 10^{16}$ cm^{-3} this requires that τ_e be shorter than 15 ps. Recent experiments on picosecond photoconductors have demonstrated τ_e as small as 1 ps in III-V materials.[6] In these experiments, it has also been proven that the techniques used to reduce τ_e, e.g., ion bombardment, affect very little the transport properties of the minority carriers. Therefore, the assumption that $\Delta t \ll \tau_e$ can still be valid. If $\alpha\Phi\tau_e$ exceeds the doping concentration, the hole conductivity will increase and V will diminish, as is evident from Eq. (2). We emphasize that the steady-state polarization effect was not observed in the experiments[3] because τ_e was too long.

The basic structure of the PVT is schematically illustrated in Fig. 2. The superlattice consists of N periods, as shown in Fig. 2(a). Under the radiation, all periods are polarized with an internal field E, generating a voltage Ed. These voltages add up constructively, producing a total potential difference V, which is applied to the FET gate. Figure 2(b) shows the cross section of a PVT with an n-channel transistor. The device can be fabricated by growing the photovoltaic structure on top of a standard FET. Under the radiation, both the gate potential with respect to the channel, and the channel carrier concentration n_s are modulated. By reversing the order by layers in Fig. 1, the PVT can be designed as either an enhancement mode or a depletion mode device.

Let us now discuss the efficiency and the speed of the PVT, using a simplified equivalent circuit that is adequate in the limit when $\alpha\Phi\tau_e$ is lower than the doping concentration. The rise and fall time of E is determined by Maxwell's dielectric relaxation time $\tau_M = \epsilon/ep\mu_p$, where ϵ is the material permittivity. This can be modeled by an equivalent circuit containing a current source I, a capacitor C, and a resistor R, defined (for a device of area A) by

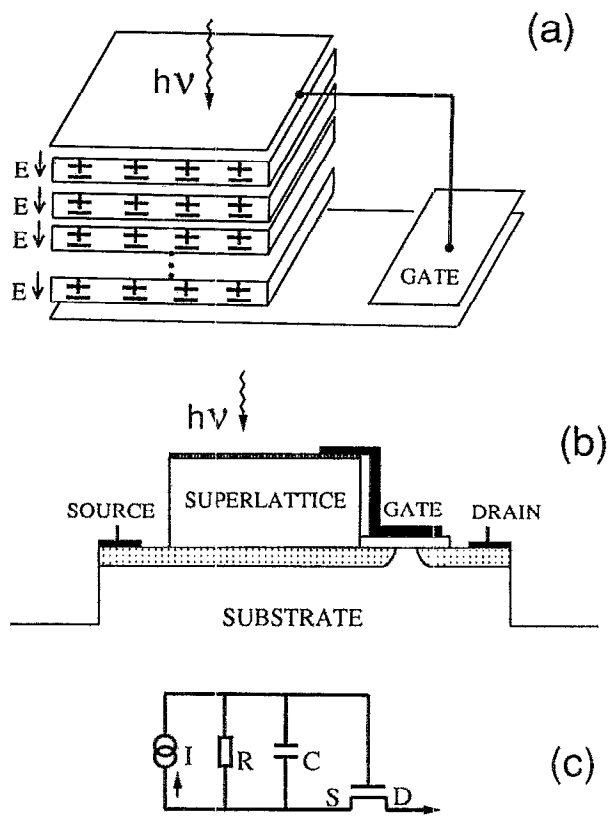

FIG. 2. Integrated photovoltaic transistor: (a) schematic diagram, (b) structure cross section, (c) simplified equivalent circuit.

$$C = \frac{\epsilon A}{Nd}, \quad R = \frac{Nd}{ep\mu_p A}, \tag{3}$$

so that $RC = \tau_M$. The current source produces a time-dependent current $I = AJ_n = Ae\alpha\Phi d$, that is modulated following the signal $\Phi(t)$. The equivalent circuit is shown in Fig. 2(c). The efficiency η of the device, defined as the number of electrons flowing through the drain of the FET per photon incident on the superlattice, is given by

$$\eta = M\alpha d, \tag{4}$$

where $M = g_m R$, and g_m is the transconductance of the FET. Also, the equivalent circuit gives the response time τ of the device as

$$\tau = \tau_g(M+1) + \tau_M, \tag{5}$$

where $\tau_g = C_g/g_m$ is the small-signal gate delay and C_g is the gate capacitance of the FET. The trade-off between the efficiency and the speed of response results from degrading the RC_g time constant when we take advantage of a high gain $M > 1$.

Substituting $N(a+d)$ for α^{-1} and taking $a \approx d$ in Eq. (4), and letting $C_g = \epsilon_g A_g/d_g$, where d_g and ϵ_g are, respectively, the thickness and the permittivity of the gate dielectric, and A_g is the gate area of the FET, we have

$$\eta = \frac{d}{2d_g}\frac{\epsilon_g A_g}{\epsilon A}\frac{\tau_M}{\tau_g}. \tag{6}$$

As an example, suppose we employ a state-of-the-art FET with an intrinsic gate delay $\tau_g = 5$ ps and a superlattice characterized by $\alpha(a+d) = 0.1$ and $\tau_M = 1$ ps, both reasonable numbers. The optimum number of periods is $N \sim 10$. The PVT will have an intrinsic response time $\tau \sim 10$ ps at $\eta \sim 5\%$ and $\tau \sim 200$ ps at $\eta \sim 100\%$. Optimization of the device toward either the faster or the more efficient mode can be done on the basis of Eq. (6).

A practical advantage of the proposed PVT is its expected tolerance to material imperfections, which results from its operation being based on a short minority-carrier lifetime. It is therefore likely that the device can be implemented heteroepitaxially on lattice-mismatched foreign semiconductor substrates, e.g., an asymmetric III-V superlattice detector, integrated with a Si FET and other circuits on the same chip.

[1] See, for example, H. Matsueda, T. Tanaka, and M. Nakamura, in *Semiconductors and Semimetals*, edited by T. Ikoma (Academic, New York, 1990), Vol. 30, pp. 231–284, and references therein.

[2] See, for example, A. S. Grove, *Physics and Technology of Semiconductor Devices* (Wiley-Interscience, New York, 1967).

[3] F. Capasso, S. Luryi, W. T. Tsang, C. G. Bethea, and B. F. Levine, Phys. Rev. Lett. **25**, 2318 (1983).

[4] S. Luryi and C. T. Liu, Phys. Rev. B (to be published).

[5] J. R. Hayes, A. R. Adams, and P. D. Greene, in *GaAsInP Alloy Semiconductors*, edited by T. P. Pearsall (Wiley-Interscience, New York, 1982), pp. 189–212.

[6] D. H. Auston, in *Semiconductors and Semimetals*, edited by R. B. Marcus (Academic, New York, 1990), Vol. 28, p. 1, and references therein.