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

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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 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. 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.\textsuperscript{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,\textsuperscript{4} the absence of a steady-state effect can be explained by the fact that the minority-carrier lifetime \( \tau_c \) was too long.

In structures with a short \( \tau_c \), 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 \( \Delta E_g \).

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 \( \alpha \) is the absorption coefficient and \( \Phi \) the incident photon flux. Photogenerated minority carriers will redistribute between layers \( a \) and \( d \) prior to the recombination. We can estimate the time period \( \Delta t \) required for the electrons to diffuse across layer \( d \) as \( \Delta t = d^2/2D_n \) where \( D_n \) is the electron diffusivity. For \( D_n \approx 250 \text{ cm}^2/\text{s} \) (corresponding to a minority-carrier mobility of \( 10^3 \text{ cm}^2/\text{V}\cdot\text{s} \) and \( d \approx 1000 \text{ Å} \), this time is well below 1 ps. For \( \Delta t < \tau_c \), 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 \( \Phi \):

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

In a steady state, the net current density must vanish, and hence \( J_p = -J_n \), where \( J_p = e \mu_p E \) is the hole current density.

![Energy Band Diagram](https://example.com/energy_band_diagram.png)

**FIG. 1.** The energy band diagram in one period of an asymmetric superlattice in thermal equilibrium (a) and under illumination (b).
sity and $p$ and $\mu_p$ 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

$$V = NEd - \frac{d}{2\mu_p \Phi} I_e$$

where $I_e = h\nu\Phi$ 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, $Na(a+d) \sim 1$, and that $a \approx d$. We see that $V$ can be enhanced by increasing $d$ or decreasing the hole conductivity. If we take $I_e = 10^4$ W/cm$^2$, and $h\nu = 0.95$ eV (corresponding to $\lambda = 1.3 \mu m$), $V$ will be over 0.3 V for $d = 1000 \AA$, assuming $p = p_0 = 10^{16}$ cm$^{-3}$ with $\mu_p = 100$ cm$^2$/V s.\(^5\)

In these estimates, we have assumed that $\alpha\Phi r_\nu < p_0$ and, therefore, $p$ is dominated by the doping. At $I_e = 10^4$ W/cm$^2$ and $p_0 = 10^{16}$ cm$^{-3}$ this requires that $\tau_e$ be shorter than 15 ps. Recent experiments on picosecond photoconductors have demonstrated $\tau_e$ as small as 1 ps in III-V materials.\(^7\) In these experiments, it has also been proven that the techniques used to reduce $\tau_\nu$, e.g., ion bombardment, affect very little the transport properties of the minority carriers. Therefore, the assumption that $N(a + d)$ can still be valid if $\alpha\Phi r_\nu$ 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 $\tau_e$ 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 $E_d$, generating a voltage $E_d$. 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 $n_e$ 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 $\alpha\Phi r_\nu$ is lower than the doping concentration. The rise and fall time of $E_d$ is determined by Maxwell's dielectric relaxation time $\tau_{M} = \varepsilon/\varepsilon_\nu$, where $\varepsilon$ 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

$$\eta = M\alpha d,$$  

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

$$\tau = \tau_g(M + 1) + \tau_M,$$  

where $\tau_g = C_m/g_m$ is the small-signal gate delay and $C_m$ 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 $a^{-1}$ and taking $a \approx d$ in Eq. (4), and letting $C_g = \varepsilon g_{A_g}/d_g$, where $d_g$ and $\varepsilon_g$ are, respectively, the thickness and the permittivity of the gate dielectric, and $A_g$ is the gate area of the FET, we have

$$\eta = \frac{d}{2d_g} \frac{\varepsilon g_{A_g}}{\tau_{g}} \tau_{M}.$$  

FIG. 2. Integrated photovoltaic transistor: (a) schematic diagram, (b) structure cross section, (c) simplified equivalent circuit.
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 $\tau_U = 1$ 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.

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