Supplementary information for "Photonic signal processing on electronic scales: active plasmoelectronic integrated circuitry"

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Both electromagnetic and electrostatic simulations were performed using the finite element method implemented within the COMSOL Multiphysics software package. First, the two-dimensional electromagnetic eigenmode problem was solved to identify waveguide modes in the geometry of interest. The obtained parameters and field distributions were used to set up boundary conditions to launch the mode in three-dimensional simulations. The maximum mesh element size in the metallic regions and in the guiding gap was set to be 7.5 nm and 5 nm, respectfully. In the ITO active area it was decreased down to 0.425 nm to resolve the electrostatic and electromagnetic field distributions in this region. The outer domain boundaries were moved away from the waveguide by at least 75 nm to eliminate their influence on the mode characteristics. The simulation results were checked to coincide for different mesh sizes and outer boundaries position. The following optical constants were used in electromagnetic simulations: $n_{Al} = 1.44 - 16i$, $n_{Au} = 0.55 - 11.5i$, $n_{Cu} = 0.606 - 8.26i$ (Ref. [1]), $n_{HfO_2} = 1.98$ and $n_{SiO_2} = 1.444$.

The characteristics of the voltage-induced free electron layer in ITO, its density and spatial distribution were found solving numerically an electro-static problem using the COMSOL finite-element method. electron density determined by the applied external To account for relationship between the induced charge distribution and the electric potential distribution in ITO, the local electron density in the conduction band n was calculated as [2]

$$n_e(x,y) = \frac{4N_c}{3\sqrt{\pi}} \left(\frac{q(E_F^0 + \varphi(x,y))}{k_B T} \right)^{3/2}, \tag{1}$$

where

$$N_c = 2 \left(\frac{2\pi m^* k_B T}{(2\pi\hbar)^2} \right)^{3/2} \tag{2}$$

is the effective density of states in the ITO conduction band and

$$E_F^0 = \frac{(3\pi^2)^{2/3} \hbar^2 n_0^{2/3}}{2m^*} \tag{3}$$

is the ITO Fermi energy, $\hbar$ is the reduced Planck constant, k_B is the Boltzman constant, T is the temperature and φ is the local potential in ITO, n_0 is the bulk free electron concentration in ITO at zero applied voltage, $m^* = 0.35 m_e$ is the effective mass of the electron, q and m_e are the electrons charge and mass. Additionally, the following relative static permittivities were used: $\epsilon^{st}_{ITO} = 9.3$, $\epsilon^{st}_{HfO_2} = 26.17$ and $\epsilon^{st}_{SiO_2} = 4.5$. The self-consistent distribution of the electron density and the electric potential in ITO, obtained in electrostatic numerical

simulations based on the above considerations (Eqs. 1–3), closely followed the exponential decay function (Figure 1(d) in the main text) for both quantities. Au, Al and Cu can produce Ohmic contacts with ITO [3–5]. The contact band structure and the associated electron density at the interface are highly dependent on the fabrication process, but with the work function differences less then ∼0.5 V, this does not significantly affect the results. It should be also noted that the nanoscale thickness of the ITO layer can considerably affect the electron statistics in it due to the partial quantum confinement. To estimate the significance of this effect, the opposite case of complete 1-dimensional quantum confinement with perfectly defined energy levels and two-dimensional electron statistics was considered with the result of qualitatively the same modulation characteristics of the device.

In the case of bulk-like statistics the charge and potential distributions can be validated using an analytical screening theory based on the Thomas-Fermi approximation, resulting in pure exponential decay for $n_e(y)$ and $\varphi(y)$ with a decay (or screening) length of [2]

$$l_{TF} = \frac{1}{2}\left(\frac{\pi}{3}\right)^{1/6}\left(\frac{\epsilon_{ITO}^{st}\epsilon_0\hbar^2}{m^* q^2}n^{-1/3}\right)^{1/2}, \tag{4}$$

where ϵ_0 is the vacuum electric permittivity. Both methods showed good agreement returning similar screening length values of ∼1 nm. At the same time, the numerical simulations treat the effect more precisely, revealing for example, that the screening length is actually voltage-dependent. Furthermore this method provides the field/charge distributions in the two-dimensional waveguide geometry.

The values of the peak electron density at the ITO interface and the screening length obtained for various gate voltages in the electrostatic simulations were used as an input for eigenmode simulations, resulting in the mode characteristics presented in Figure 2 in the main text and further in the full 3D numerical propagating mode simulations.

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