Near-infrared to visible up-conversion in a forward-biased Schottky diode with a *p*-doped channel

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Near-infrared radiation of wavelength 1.5 μm is up-converted to a visible wavelength of 818 nm by internal photoemission in a Schottky diode with a modulation *p*-doped channel. The near-infrared light incident upon the metal–semiconductor interface excites electrons from the metal into the semiconductor. The electrons then drift into the quantum well where they recombine radiatively, producing luminescence at the shorter wavelength of 818 nm. The intensity of the luminescence is strongly dependent on bias, and turns on at a forward bias of -0.7 V. © *2000 American Institute of Physics.* [S0003-6951(00)03712-8]

Since the invention of 1.5 μm emission InGaAs/InP laser diodes, methods of up-converting light from the near-infrared to the visible spectral range have evoked much interest. Up-conversion can be achieved by exciting Er^{3+} ions with infrared light and collecting the visible luminescence.[1,2] More recently, up-conversion based on other rare-earth ion-doped systems has been investigated[3–5] with the goal of creating a blue-green laser. However, despite the high conversion efficiencies of these methods, an alternative scheme based on a semiconductor material system would have the advantage of simplified integration with existing optoelectronic technologies.

Here we report a method of up-converting radiation from 1.5 μm to 818 nm, based on internal photoemission.[6] This involves the photoexcitation and recombination of carriers across a metal–semiconductor interface.[7] As shown in Fig. 1, near-infrared light of wavelength 1.5 μm is directed upon the surface of a metal in contact with a *p*-type modulation doped GaAs/AlGaAs quantum well. This results in the excitation of electron-hole pairs in the metal. In the absence of external bias, Fig. 1(a), band bending at the Schottky interface keeps photoexcited electrons from reaching the quantum well. However, if a forward bias is applied between the Schottky contact and the hole-gas channel, Fig. 1(b), the Fermi level at the metal–semiconductor interface is raised and the direction of the band bending is reversed. Under such conditions, electrons photoexcited with an energy slightly lower than the Schottky barrier height tunnel into the semiconductor where they drift towards the quantum well. The electrons are captured in the quantum well where they recombine radiatively, resulting in luminescence at an energy

corresponding to the lowest electron-hole transition of the quantum well. This emitted light has greater energy than the energy of the incident photons needed to lift an electron across the Schottky barrier, therefore up-conversion of near-infrared to visible light occurs. During this process the phase information of the incident photons is lost due to scattering events, therefore the up-converted 818 nm light is incoherent in relation to the incident 1.5 μm radiation.

The heterostructure used for this study was grown by molecular beam epitaxy and the layer structure is as follows: semi-insulating GaAs substrate/GaAs undoped (500 nm)/ $Al_{0.3}Ga_{0.7}As$ undoped (250 nm)/δ-doped Be layer/ $Al_{0.3}Ga_{0.7}As$ undoped (5 nm)/GaAs quantum well undoped (10 nm)/$Al_{0.3}Ga_{0.7}As$ undoped (5 nm)/δ-doped Be layer/ $Al_{0.3}Ga_{0.7}As$ undoped (40 nm). The level of Be doping in each of the δ layers is adjusted to achieve a carrier concentration of 3×10^{11} cm^{-2} in the channel, as was confirmed by
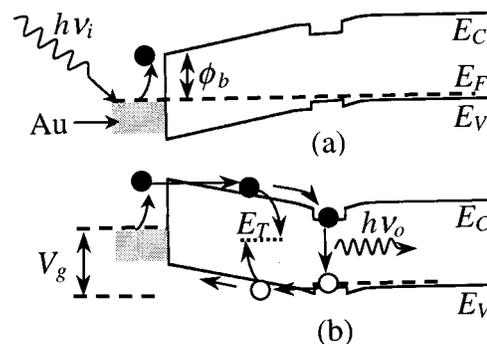

FIG. 1. Energy band diagram of a metal–semiconductor Schottky diode with a *p*-doped quantum well, (a) without bias and (b) with forward bias. E_c is the bottom of the conduction band, E_v is the top of the valence band, E_F is the Fermi level, ϕ_b is the Schottky barrier height, $h\nu_i$ is the incident photon energy, $h\nu_o$ is the output photon energy, and E_t is the trap level for nonradiative recombination.

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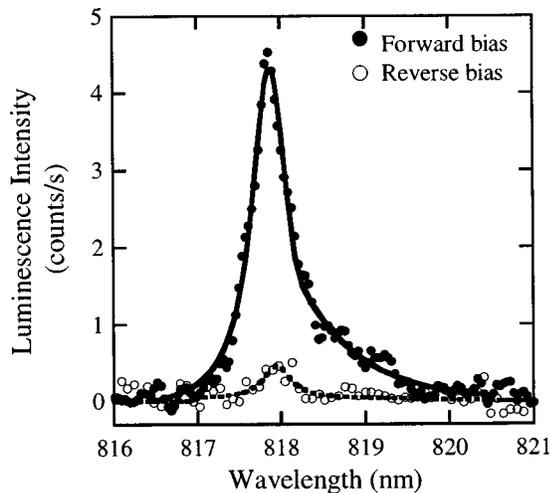[c)]Electronic mail: jrac@hermes.cam.ac.uk

FIG. 2. Luminescence spectra of light generated with top-contact voltages of −1 (forward bias) and +1 V (reverse bias). The solid and dashed lines serve to guide the eye. The excitation power at 1.5 μm wavelength is 5 mW.

FIG. 3. Intensity dependence of the luminescence produced with −1 (forward bias) and +1 V (reverse bias) applied to the top contact of the device.

Hall measurements at 4.2 K. Standard photolithographic methods were used to define a $400\,\mu\text{m} \times 80\,\mu\text{m}$ mesa on which ohmic contacts were formed to the hole gas, with 175 nm of Au/Be covered by 150 nm of Au alloyed at 490 °C for 80 s. A $50\,\mu\text{m} \times 50\,\mu\text{m}$ semitransparent Schottky contact was formed on top of the mesa by evaporating 15 nm of Au at 5×10^{-7} mbar.

All measurements were made at 4.2 K in a continuous-flow cryostat. The source of the 1.5 μm (0.8 eV) radiation was a 100 fs pulse-width Ti:sapphire-pumped optical parametric oscillator. The luminescence was collected using a single-pass spectrometer with a liquid nitrogen cooled charge coupled device detector.

Figure 2 shows the luminescence from the device under forward and reverse biases, corresponding to top-contact voltages of −1 and +1 V, respectively. The peak is centered at 817.8 nm, which is the same wavelength as the value obtained from photoluminescence measurements using above-band-gap illumination. Luminescence under forward bias is possible because the band bending allows electron injection from the transparent top metal contact into the semiconductor. Some luminescence is obtained under reverse-bias conditions, even though the injection of electrons is not possible. We can understand this by considering power-dependence measurements of the peak luminescence intensities under forward and reverse biases, Fig. 3. The forward-bias luminescence has a near-linear power dependence, indicating a single-photon absorption process. By contrast, the intensity of the reverse bias luminescence peak increases quadratically with incident power. The luminescence peak at reverse bias is observed also when the exciting laser spot is to the side of the Schottky contact. These considerations imply that the reverse-bias luminescence results from two-photon absorption in the quantum well.[8,9] It might be thought possible that the luminescence results from two-photon absorption in the AlGaAs barrier layer, however, this mechanism can be excluded as the band gap energy in this region is greater than twice that of the incident photon energy.

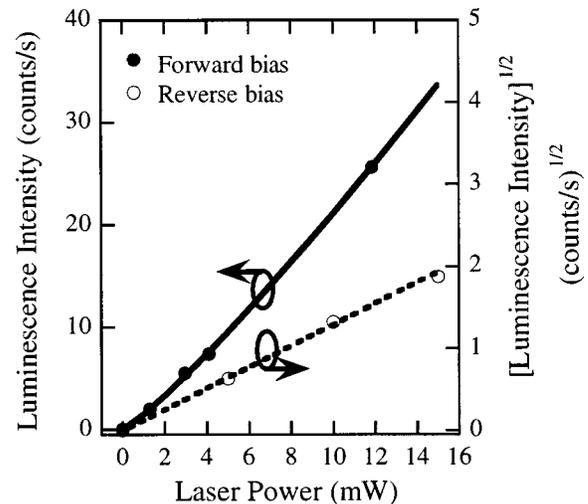In the absence of illumination, the device displays a typi-cal diode current–voltage characteristic, as shown in Fig. 4, trace (i). The photocurrent (the difference in current, with and without illumination) is shown in trace (ii), and plotted again, magnified 500× in trace (iii). Under reverse bias (with a positive voltage on the Schottky contact) the photocurrent is positive. As the Schottky contact voltage is reduced the photocurrent decreases and becomes zero at −0.3 V. For more negative contact voltage the photocurrent changes sign and begins to increase in magnitude. Under forward bias conditions the photocurrent is typically 5% of the dark current at 5 mW pump power. Trace (iv) shows the bias dependence of the luminescence. As described earlier, under reverse bias, two-photon background absorption luminescence is observed. Under forward bias, the luminescence intensity begins to increase once the Schottky contact voltage is below −0.7 V, until the luminescence decreases at a bias of
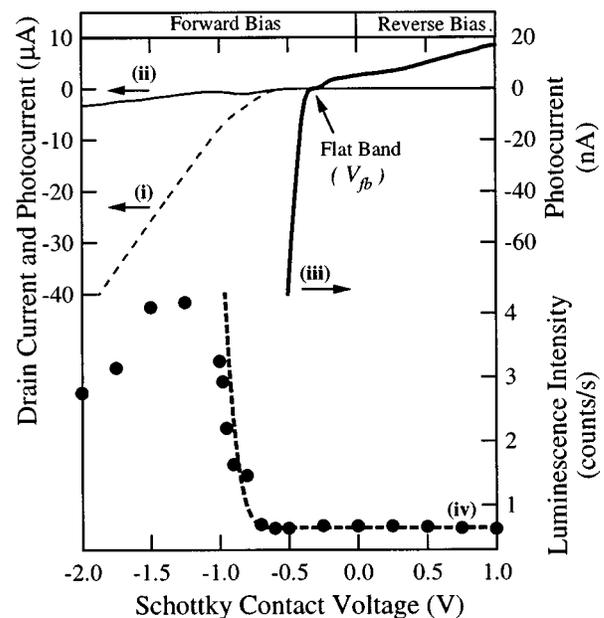

FIG. 4. Dependence on top-contact voltage of (i) dark current, (ii) photocurrent, (iii) photocurrent multiplied by 500, and (iv) luminescence intensity. Dashed curve is derived from an electron tunneling model. Power of excitation laser is 5 mW.

−1.2 V. Between −0.3 and −0.7 V photocurrent is observed without corresponding luminescence.

We can understand this behavior by considering the band diagram in Fig. 1(a). Under reverse bias the direction of band bending allows only photoexcited holes to drift into the semiconductor. Since electron injection is needed to produce light, no luminescence is observed despite a photocurrent being measured. As forward bias is applied, Fig. 1(b), the internal field decreases and the bands flatten. At flatband (V_{fb} = −0.3 V) neither electrons nor holes drift across the semiconductor and the photocurrent becomes zero. Beyond flatband two processes contribute to the photocurrent. First, the incident light photoexcites holes out of the quantum well, which then drift into the metal gate. This is a nonradiative process as no electrons are excited in the conduction band by the sub-band-gap energy excitation. Second, electrons add to the current when they enter the semiconductor after photo-excitation from the metal. This results in luminescence, as the electrons then recombine with holes in the quantum well. However, luminescence is not observed until a bias of −0.4 V below flatband (i.e., −0.7 V) because the energy of the incident 1.5 μm photons (0.8 eV) is not sufficient to excite the electrons over the Schottky barrier (1 eV).[10] Instead, they must tunnel through the barrier into the semiconductor. This tunneling can be modeled using Wentzel–Kramers–Brillouin (WKB) approximation,[11] and is given by

$$P = \exp\left[\frac{-4(2qm^*)^{1/2}\gamma^{3/2}}{3\hbar E}\right], \tag{1}$$

where m^* is the effective mass of the electron, γ is the energy difference between the top of the barrier and the energy of the tunneling state, and E is the electric field in the device. Assuming a constant density of states at the metal–semiconductor interface, the total tunneling probability (which includes all energetically allowed transitions) can be calculated by integrating Eq. (1), with respect to γ. From this the luminescence intensity (L) can be calculated using

$$L(V_g) = N\omega\sigma_1\sigma_2 \int_{\phi_b - h\nu_i}^{V_g - V_{fb}} \exp\left[\frac{-4(2qm^*)^{1/2}\gamma^{3/2}}{3\hbar E}\right] d\gamma, \tag{2}$$

where N is the average number of photoexcited electrons available for tunneling in the illuminated region, ω is the electron tunneling attempt frequency, σ_1 is the internal electron-to-photon conversion efficiency for the electrons that reach the semiconductor, and σ_2 is the collection efficiency of the experiment. The product $\sigma_1\sigma_2$ was obtained by directly exciting carriers in the upper AlGaAs region with 3 eV blue light and measuring the luminescence. Using this model, the luminescence can be calculated as a function of

bias, trace (iv). The model fits well to both the turn-on voltage and the rate at which the luminescence increases with bias. However, the decrease in luminescence intensity observed beyond a forward bias of −1.2 V is not predicted. We propose that the decrease in luminescence is due to an increase in the number of available trap states in the upper AlGaAs region with increasing bias. Since there is also a large hole current through this region, the probability of trap-assisted indirect recombination in the AlGaAs increases with the number of trap states. This in turn reduces the fraction of electrons in the semiconductor which reach the quantum well and recombine radiatively. This nonradiative process is shown in Fig. 1(b). A similar decrease in luminescence was also observed in the 3 eV AlGaAs excitation experiment, which further supports nonradiative recombination in the AlGaAs layer as the mechanism responsible for the decrease in luminescence.

In summary: an up-conversion device based on a *p*-doped quantum well structure has been demonstrated. Incident light of wavelength 1.5 μm photoexcites electrons from a semitransparent gold Schottky gate into a semiconductor. Under forward-bias conditions the electrons drift into a *p*-doped quantum well where they combine radiatively. This results in luminescence at the shorter wavelength of 818 nm. Since the device is based on a semiconductor material system, there are many potential advantages over existing up-conversion devices. These include the possibility of fabricating large arrays, and integrating structures with existing III–IV optoelectronic technologies.

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