# Room-temperature electro-optic up-conversion via internal photoemission

K. J. Russell[a)]
*Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138*

Ian Appelbaum
*Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138 and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

H. Temkin
*Department of Electrical Engineering, Texas Tech University, Lubbock, Texas 79409*

C. H. Perry
*Department of Physics, Northeastern University, Boston, Massachusetts 02115*

V. Narayanamurti
*Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138*

M. P. Hanson and A. C. Gossard
*Materials Department, University of California, Santa Barbara, California 93106*

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We describe the fabrication and operation of a device which performs linear optical up-conversion at room temperature. The mechanism for up-conversion is based on internal photoemission from a Schottky contact. We then describe the voltage dependence of this device and interpret it in terms of total energy conservation. Although an AlGaAs/GaAs system is employed here, the functionality is not material-specific and therefore should be widely applicable to different materials systems, such as GaN/InGaN. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1571981]

Heterostructure devices have long been used for linear up-conversion of radiation.[1–3] These devices invariably consist of two structures in series: one section for photodetection and another for luminescence. The principal distinction between the different devices has been the method of photodetection; with only one exception,[4] a light-emitting diode (LED)-type structure has produced the resulting luminescence.

Two photodetection mechanisms have been more developed than the others: interband photo-excitation,[1–3] and intersubband photoexcitation achieved through use of a quantum well infrared photodetector (QWIP).[5] Two other mechanisms have also been used: that by Sandhu *et al.*[4] and that by Hiramoto *et al.*[6] Sandhu *et al.* demonstrated an up-conversion process that used internal photoemission from a Au Schottky contact. In that case, the up-converted luminescence was produced from electrons injected into a two-dimensional hole gas rather than into an LED structure. This device was able to operate at low bias voltages, but only inefficiently and at very low temperatures (4 K). Hiramoto *et al.* used a film of photoresponsive amorphous silicon carbide ($a$-SiC:H) in conjunction with an organic LED. Because of the large bias voltages required for operation, this device can be thought of as a photoresponsive resistor modulating the bias voltage across an organic LED.

Using a system similar to that of Sandhu *et al.*, we present an up-conversion device that uses internal photoemission from a Schottky contact for photodetection. Our device produces an easily measured signal at room temperature and at voltages significantly less than the band-gap energy. We also present an interpretation of the device operation that provides for a straightforward analysis of the voltage dependence of the luminescence.

Our device was grown via molecular-beam epitaxy with the following structure: heavily doped $p$-type GaAs substrate, 300-nm $p$-type GaAs buffer layer doped to $5\times10^{18}$ cm$^{-3}$, 300-nm $p$-type $Al_{0.30}Ga_{0.70}As$ doped to $5\times10^{18}$ cm$^{-3}$, 10-nm GaAs undoped QW, 100-nm $n$-type $Al_{0.30}Ga_{0.70}As$ doped to $2\times10^{17}$ cm$^{-3}$, and a 20-nm $n$-type GaAs cap layer doped to $2\times10^{17}$ cm$^{-3}$. All $n$-type doping is with Si, all epitaxial $p$-type doping is with Be, and substrate doping is with Zn. A structural diagram of our device is given in the inset of Fig. 1.

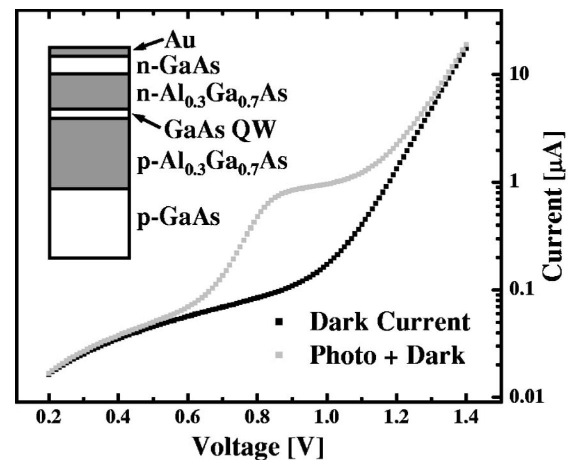


FIG. 1. Current–voltage characteristics of the device with and without sub-band-gap photoexcitation. A substantial photocurrent is generated for biases greater than ≈0.7 V. The inset is a schematic diagram of our device structure (not to scale).

[a)]Electronic mail: krussell@deas.harvard.edu


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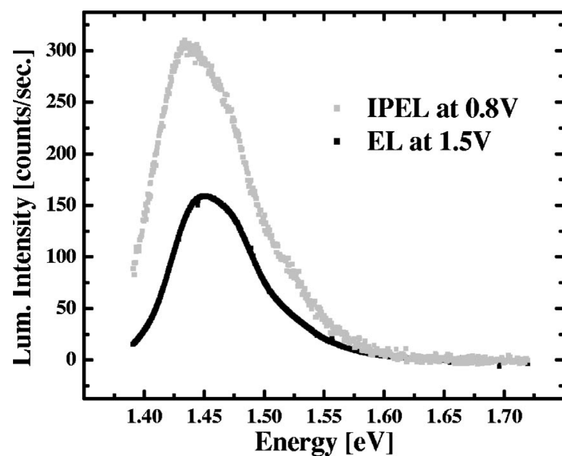


FIG. 2. Luminescence spectra for EL as well as IPEL. The IPEL signal is significantly larger that the EL signal, even at approximately half the applied bias.

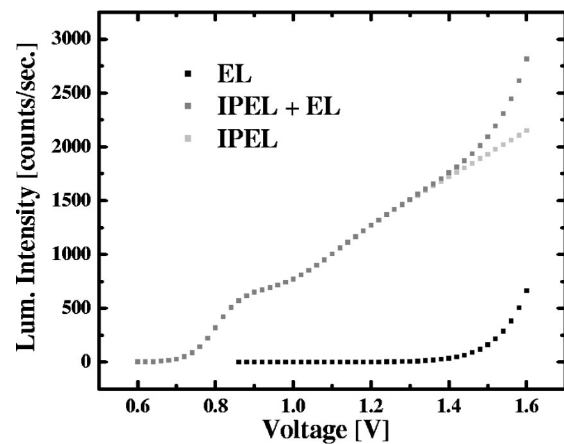


FIG. 3. Voltage dependence of EL, IPEL+EL, and IPEL alone. Sub-band-gap optical excitation produces observable luminescence at significantly lower voltages than thermal excitation.

The structure parameters were chosen to provide an $n$-type Schottky interface at the surface and a hole-rich recombination region in the GaAs QW. The doping at the surface must be relatively light to reduce Schottky leakage, but not so light that the surface depletion region extends into the $p-i-n$ junction. The $p$-type doping level must be significantly higher than that of the $n$-type region to compensate the electron population in the QW. These requirements lead to the asymmetrically doped $p-i-n$ heterostructure.

The wafer was processed using standard photolithographic techniques. After patterning, the surface was cleaned with dilute $NH_4OH$, and 100 Å of Au was deposited at high vacuum to form a $200\times400\ \mu m^2$ Schottky contact. The thickness of this Schottky contact was chosen as a compromise between absorption of the excitation light and transmission of the up-converted light. The sample was then processed into device mesas 2 $\mu$m high and of area $300\times600\ \mu m^2$ by patterning with photolithography and etching with $NH_4OH/H_2O_2/H_2O$ 1:1:5 for 60 s. Electrical contact to the Au was provided by a Cr–Au layer forming a lead to an insulating $Al_2O_3$ bonding pad. All subsequent measurements were done at room temperature with this contact as electrical ground. Electrical contact to the substrate was made by cold-pressing an In contact to the back surface.

Figure 1 shows the current–voltage characteristics of the resulting device with and without sub-band-gap illumination. Under conditions used here, the Schottky diode was reverse biased, while the $p-i-n$ junction was forward biased. Illumination was provided by a single 25-mW diode laser (Lasermate LTG-980-25), emitting at 980 nm (1.26 eV), coupled into an optical fiber whose emitting end was in close proximity to the surface of the device. The photocurrent is clearly suppressed for biases below $\approx 0.8$ V.

When a bias of approximately 1.5 V was applied across the sample, electroluminescence (EL) was observed with a center wavelength of 850 nm (1.42 eV). This luminescence was collected at normal incidence through the Au contact by a 400-$\mu$m core diameter high-numerical-aperture (0.39) optical fiber placed in close proximity to the device (parallel to the illumination fiber). Figure 2 shows a spectrum of this EL at a sample bias of 1.5 V. This and all other luminescence spectra were taken with a Thermo-Oriel MS257 spectrograph with an Instaspec™ IV CCD camera, a diffraction grating with 600 lines/mm, and a blaze wavelength of 400 nm.

Without applied bias, sub-band-gap illumination did not result in any luminescence because the photon energy was too low to induce the required band-gap excitation. However, the device did produce band-gap luminescence at bias voltages greater than $\approx 0.7$ V, still significantly less than the band-gap energy. An example spectrum of the internal photoemission luminescence (IPEL) at 0.8 V bias is given in Fig. 2.

Figure 3 shows the voltage dependence of the magnitude of the luminescence both with and without sub-band-gap illumination. Both plots are shown on the same scale to indicate the relative efficiencies. EL can be observed for biases near the band-gap energy (1.42 eV),[7] but with photoexcitation, luminescence was observable at substantially lower voltages. After an abrupt increase at $\approx 0.8$ V, the intensity of the luminescence with photoexcitation increased linearly with voltage. At higher voltages, the EL signal added to the IPEL signal, causing the total luminescence (IPEL+EL) to increase superlinearly. However, by subtracting the EL signal, we see that the signal due to photoexcited carriers alone (IPEL) continued to increase linearly.

For all bias voltages, the intensity of the EL is significantly less than that of the IPEL as a result of the rectifying nature of the Schottky contact. This leakage-current-limiting feature enhanced the photoresponse of the device, as is clear from a comparison of current–voltage characteristics with and without photoexcitation (Fig. 1). The large increase in photoresponse at $\approx 0.7$ V coincides with the large increase in IPEL, confirming that the Schottky contact is performing its function as a gate for photoexcited electrons. This is further confirmed by data collected at low temperatures (80 K). Under such conditions, EL is not observed even at a bias of 2.2 V, whereas IPEL can be observed with only a 0.7-V bias. Thus, we can conclude that electrons must be either thermally or optically excited in order to overcome the Schottky barrier and recombine in the QW.

We interpret the voltage dependence of the luminescence in light of total energy conservation, as depicted in Fig. 4. It would be unphysical, assuming linear response from a passive device in equilibrium, to expect that high energy ($h\nu_o$

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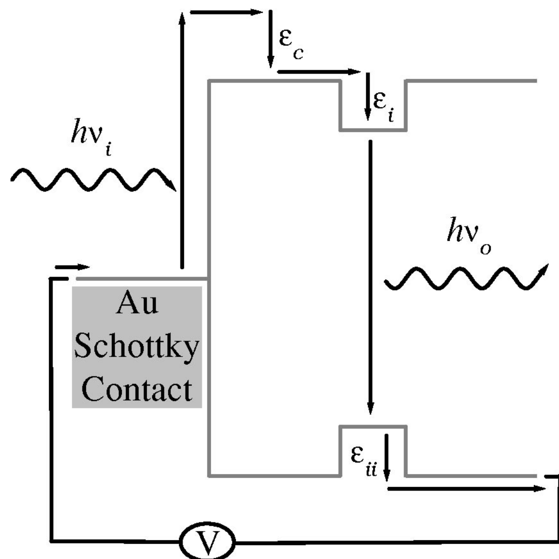


FIG. 4. Band diagram schematic for our device. At IPEL threshold ($\approx 0.8$ V), energy added to the system ($h\nu_i + \mathrm{V}$) equals the energy dissipated ($h\nu_o + \varepsilon_c + \varepsilon_i + \varepsilon_{ii}$).

$= 1.42$ eV) photons will be produced directly from low energy ($h\nu_i = 1.26$ eV) photons. The extra energy must be supplied externally; in this case, by means of an electrical bias ($V$).

The effective Schottky barrier from the Fermi energy in the Au to the surface conduction band minimum of the $Al_{0.30}Ga_{0.70}As$ $n$-type layer is $\approx 1.0$ eV, as determined by self-consistent calculations and published values of band offsets.[8,9] The difference between the maximum energy of the photoexcited electrons and the effective Schottky barrier is then $\varepsilon_c \approx 0.25$ eV. This energy is lost in thermalization to the $Al_{0.30}Ga_{0.70}As$ conduction band. Additional energy is lost as both the hole and electron thermalize in the quantum well ($\varepsilon_{ii}$ and $\varepsilon_i$, respectively). This energy is equal to the difference in band-gap energies between $Al_{0.30}Ga_{0.70}As$ and GaAs (approximately 0.35 eV).[7] The amount of energy put into the system (1.26-eV photoexcitation + 0.8 eV bias) minus the energy lost due to thermalization (0.6 eV) is approximately the amount of energy extracted from the system (1.45 eV) in the form of luminescent photons. More precise quantitative analysis of the voltage dependence is difficult to do because of thermal effects; the IPEL threshold becomes sharper with lower temperature. In addition, the height of the effective Schottky barrier is difficult to determine accurately because of complex band bending due to the confluence of the Schottky contact and $p-i-n$ junction depletion regions.

This straightforward explanation of the thresholds presents a different perspective than that given in Ref. 4. The observed threshold near 0.7 V presented in that work was attributed to electron tunneling through the edge of the Schottky barrier. Since our experiment uses sub-band-gap but super-Schottky illumination, tunneling plays a negligible role in the photoemission process, so the fact that we observe a similar threshold suggests that the agreement between the tunneling model and data in Ref. 4 was coincidental. Energy conservation, as discussed earlier, provides a more compelling reason to expect a threshold where it is observed.

It is possible to envisage more sophisticated devices based on the idea discussed here. As we did not attempt to optimize photoresponse or luminescence efficiency, both aspects could be improved. In addition, the same structure could be implemented in different materials, making devices that respond to and emit at different wavelengths. As an example, a similar device made of GaN/InGaN could be grown on a transparent substrate (sapphire) to make it possible to up-convert from near-infrared to visible light. This could be implemented as an active, pixelless infrared detector. Allard *et al.* used a QWIP/LED up-conversion system for a similar purpose, but this required a more complicated collection geometry, and, since it up-converted from infrared to near-infrared, it required another device (a CCD camera) to view the image produced by the up-conversion.[10]

In conclusion, we have presented a device for up-conversion of radiation that should be directly applicable to other materials, making it straightforward to up-convert to and from a variety of wavelengths. We have also presented an interpretation of device operation in terms of energy conservation that greatly simplifies the analysis of voltage dependence.

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