Question 1 [25 marks]:
   a) Provide a cross-sectional diagram of three heterojunction devices using different materials and/or structures. These could be two- or three terminal (or more) devices from any year, but must not be identical structures. Provide the relevant reference for each structure. [6 mark]

A simple way to tackle this question is to search for something like “heterojunction AND device” over all years and start looking into papers.

If you simply order by “Times Cited” you may end up with a lot of papers on similar topics in high-impact areas, such as organic semiconductors and perovskite solar cells. Instead you could just select a random year and order by “Times Cited” to eliminate some of the more recent topics. Alternatively, you could order by date and just start going through the papers. However you approach the problem there are many possible answers. I have provided three below.

Device 1:


Device 2:

**Device 3:**


b) Name a material which has been used with silicon in a heterojunction. Provide a cross-sectional diagram, band diagram, or microscope image showing the layers, and a reference. [3 mark]

There are only a few options here because lattice-matching on group IV semiconductors like silicon is not as versatile as on III-V semiconductors such as GaAs. If you rely on the highest cited articles with “Silicon AND Heterojunction” in the topic you may end up with a lot of non-relevant studies, such as organic bulk heterojunctions which use a silicon oxide layer. One option is to use the same search term for the title.

The strategy I used is to search for “Silicon AND Heterojunction” but restrict the search to papers published 1995 and before. This is because silicon was much more heavily before the year 2000 than it is today, and we will be able to eliminate much of these highly cite perovskite and organic semiconductor papers this way.
There are a few options such as silicon-carbide, germanium of a silicon-germanium alloy. Below is a band diagram of a Si/SiGe/Si heterojunction transistor.


c) Briefly describe what is meant by a bulk heterojunction. Provide a representative diagram from a paper of what a bulk heterojunction is (can be an cartoon / illustration), with an appropriate reference.[3 marks]

This question may require going through a large number of papers to find an appropriate figure. I just used the following search query and ordered by times cited, then went from top to bottom, scanning the document until I found the appropriate figure.

Quite a few papers just had a picture of the device structure but no schematic / diagram of what the bulk heterojunction itself was. The first is shown below.

A bulk heterojunction is a disordered interpenetrating network of two different semiconductors (normally solution processable organics). A common mixture is PCBM and P3HT; a fullerene and a polymer.

d) Name a device besides flash memory which exploits Fowler Nordheim Tunneling. Include a reference to the paper.[2 marks]

It turns out there are a wide range of devices which use Fowler Nordheim Tunneling. I just used the simple search term below and order by times cited.

While a number of papers just look at the physics of the process, some do described practical applications. The second article was a review article on “Single-Electron Devices and Their Applications” which is a class of devices which process information using a single electron at a time.

**Single-Electron Devices and Their Applications**

KONSTANTIN K. LIKHAREV, MEMBER, IEEE

*Invited Paper*

e) Name the semiconductor materials used in a resonant tunneling diode. Provide a reference.[2 marks]

A simple strategy is to use the below search term:

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I just took the most highly cited paper, which was this one:

**Spin-Filter Device Based on the Rashba Effect Using a Nonmagnetic Resonant Tunneling Diode**

Takaaki Koga,* Junaka Nitta, and Hideaki Takayanagi

**NTT Basic Research Laboratories. NTT Corporation, Atsugi, Kanagawa, 243-0198 Japan**

Supriyo Datta

**School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907**

(Received 1 October 2001; published 12 March 2002)

If you open up a paper like this you can often expect to see a structure, which there was, but the materials were not listed. Instead they were described in Table 1.

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<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>$m^*/m_0$</th>
<th>$E_b$ [eV]</th>
<th>$\epsilon_s/\epsilon_0$</th>
<th>$\Delta$</th>
<th>Thickness [Å]</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter 1,3</td>
<td>In$<em>{0.52}$Al$</em>{0.48}$As</td>
<td>0.075</td>
<td>1.66</td>
<td>12.46</td>
<td>0.309</td>
<td>N.A.</td>
<td>60</td>
<td>4 x 10$^{16}$</td>
<td>2 x 10$^{19}$</td>
</tr>
<tr>
<td>Well 1,2</td>
<td>In$<em>{0.52}$Ga$</em>{0.48}$As</td>
<td>0.041</td>
<td>0.783</td>
<td>13.1</td>
<td>0.328</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Barrier 1,3</td>
<td>In$<em>{0.52}$Al$</em>{0.48}$As</td>
<td>0.075</td>
<td>1.66</td>
<td>12.46</td>
<td>0.309</td>
<td>35</td>
<td>1.37 x 10$^{16}$</td>
<td>6.85 x 10$^{16}$</td>
<td>0</td>
</tr>
<tr>
<td>Collector</td>
<td>In$<em>{0.52}$In$</em>{0.48}$As</td>
<td>0.041</td>
<td>0.783</td>
<td>13.1</td>
<td>0.328</td>
<td>N.A.</td>
<td>~1 x 10$^{17}$</td>
<td>~1 x 10$^{17}$</td>
<td>~1 x 10$^{17}$</td>
</tr>
</tbody>
</table>

$\Delta E_r$ [eV] = 0.270, 0.165, 0.030

I.e. the device is made from InAlAs and InGaAs with various alloying ratios.

f) Name a device besides resonant tunneling diodes which exhibits negative differential resistance (NDR). Provide a current-voltage plot showing the NDR behavior, and the reference.[3 marks]

It is possible you are already aware of such a device, in which case you could just search for “Memristor”. Otherwise, you are probably best simply search for “negative differential resistance” as the search term:

While there a range of a devices that exhibit NDR, if you were to order by times cited you will find that molecular junctions come to the top. These are devices which has a single molecule between the two electrodes, as shown here:

These devices behave in a similar way to resonant tunneling diodes but are not RTDs.

The top paper is from a collaboration between Yale and Rice published in 1999. The NDR is simply part of an IV curve where the gradient is negative: i.e. the resistance falls with increasing voltage. This is shown in Figure 2 of this paper:

g) Name a semiconductor growth technique which has been used to fabricate quantum cascade lasers. Provide a reference. [2 marks]

For this one you are probably going to have to download a paper, go into the experimental section and read what technique was used. The most simple search term is just the below:

![Web of Science search for Quantum Cascade Laser](image)

As usual, I ordered by times cited. I didn’t actually choose the top one in this case; instead I used the second entry – the original report of a quantum cascade laser from 1994.

Unfortunately OSU does not provide access to this article so you would not be able to read the experimental section. Luckily however, the technique is mentioned in the abstract. So you have your answer.
There may be quantum cascade lasers fabricated via other means (perhaps ALD), but \textit{molecular beam epitaxy (MBE)} is likely to be the most common.


\textbf{h)} Provide a brief (between a quarter of a page and half a page) description of a challenge associated with one of the following technologies. Please provide references to any papers you used when attempting answer this question. [4 marks]

a. Resonant tunneling diodes.

b. Quantum cascade lasers.

c. Solar cells based on 2-dimensional materials (e.g. graphene, hexagonal boron nitride).

d. Ballistic diodes.

This will require a little more reading than the other questions, since there is unlikely to be a paper on “Challenges in Quantum Cascade Lasers” for example. There is no single answer to this question of course, and you will be graded based on the logic of your statements and how they relate to what is presented in the references you provide. You will not be penalized if you make a statement from a paper which has subsequently been found to be incorrect. It is sufficient to provide a single reference if all the relevant information is contained within this paper. This is likely to be the case for review articles on a subject.